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Bottleneck Identification and Analysis for an Underground Blast Cycle Operation

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Abstract

Increasing demand for raw materials and base metals together with severe environmental regulations influence mining operations to be more economic, competitive, and sustainable. Since mining involve numerous operations which difficulty ranges from simple to very complex, each of them need proper design, performance and optimization. Mining operations including activities within blasting cycle affects productivity the most, and thereby their planning and performance is the most important from production point of view. Since blasting cycle operations include many complex activities where many inner and outer factors have an influence on operating efficiency, it is crucial to thoroughly investigate the system every time new problems arise or when looking for improvements.

According to Theory of Constraints every production system has at least one bottleneck. Blast cycle operations may be treated as a system regarding production. Therefore, there is/are constraint(s) which should be solved and bottleneck(s) should be debottlenecked. It is in demand to properly identify constraints within the blasting cycle operations and subsequently take measures to improve them for enhanced production results. Due to system complexity and presence of many factors and variables it is efficient to use some techniques that will facilitate analysis. Discrete event simulation approach makes it possible to analyze underground mining operations and identify critical points where improvements could be made.

In these thesis computer simulation approach, together with concepts derived from theory of constraints were used to identify bottleneck and perform its analysis. Many simulations were conducted to search for improvements and indicate those with the highest potential for development and increase of production.

Keywords bottleneck, theory of constraints, blast cycle, blasting operations, computer simulation, discrete event simulation,

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IV. List of Abbreviations

BP	Bolting Rigs Performance
BRM	Bolting Rigs Maintenance
CAD	Computer Aided Design
CCPM	Critical Chain Project Management
CCR	Capacity Constraint Resource
DBR	Drum-Buffer-Rope
DES	Discrete Event Simulation
FY	Fiscal Year
KPI	Key Performance Indicator
MOC	Mine-Operator-Center
MTBF	Mean Time Between Failures
MTTR	Mean Time to Repair
OPT	Optimized Production Timetables
PM	Preventive Maintenance
POOGI	Process of Ongoing Improvement
ROI	Return on Investment
TOC	Theory of Constraints
TP	Thinking Process

1 Introduction

Over the last few decades, as the world economies and industries have been growing rapidly, there has been an increasing demand for base metals and minerals. To meet supply requirements, the mining industry with both underground and surface operations have been rising production rates by developing its operating capabilities regarding economic, environmental, and safety factors. The use of new technology and innovative equipment has also contributed substantially to set higher production levels and provision of safer working conditions. However, every year the mining industry is facing new difficulties as the situation is becoming more challenging due to deeper levels of exploitation or environmental limitations. In the forthcoming years, there will be even higher need to increase operating efficiency, therefore, up to date solutions are mandatory to be implemented. Even though new technologies and machinery facilitate achieving production objectives, their impact on managerial policy and decision making has been very narrow. There are many companies and providers who supply mining industry with top class equipment and technology for minerals exploration, exploitation, material handling and processing, however, not many of mining and mining-related companies offer solutions for management assistance and support in making strategic operating decisions. During mining operations, many problems may emerge. Sometimes, causes of these problems or their terminology may be misunderstood. Bottleneck is one terms which should be thoroughly studied and well considered. Inaccurate understanding of bottleneck terminology may lead to unnecessary mitigating attempts instead of effective actions.

Bottleneck is generally considered as the factor which limits the overall performance of the production system by reducing system's output capabilities. In mining industry, exploitation systems are designed up to known bottlenecks. These bottlenecks are addressed to the processes with the lowest capacities in the whole production circle. However, not all the processes are able to work at maximum rates and maximum capacities, therefore, bottleneck may tend to move between different processes. This situation makes it even harder for the management to identify and focus on a real bottleneck root cause.

Majority of the scientific papers regarding bottleneck identification and bottleneck mitigation concern other industries than mining. However, some authors do write about bottleneck problems in the mining industry. Most of the cases describing bottleneck in mining involve Theory of Constraints (TOC) and discrete event simulation (DES) methodology to find solutions for bottleneck problems in mining and mining-related operations.

The TOC concept was first introduced by Eliyahu Goldratt in 1987 for manufacturing industries. There has been an increased interest in application of TOC in mining industry. TOC focuses on bottleneck identification, its maximum exploitation and management. TOC methodology also helps to identify the real bottleneck, which is commonly misinterpreted in mining operations and may support bottleneck managerial policy. TOC as bottleneck theory was supported by DES (Baafi, 2015) to support analysis of complex operations and to propose solutions for bottleneck mitigation or its improvements.

Furthermore, computer simulation has found its application in almost all types of industries and is widely used in numerous operations. Computer based simulation and particularly DES is commonly used in the mining industry and plays an important role in processes evaluation. Simulation techniques are beneficial tools in mining, because they allow to simulate future operations and analyze them from different points of view. Computer based simulations are helpful in decision making. Additionally, they may support analysis in planning and optimization objectives of processes like ore handling, processing, and fleet management.

Both TOC methodology and DES may be very helpful in accurate bottleneck identification and support mine management in decision making to mitigate and solve bottleneck problems. Furthermore, TOC and DES which allows quite fast execution of simulations of complex processes, may contribute to modifications in mining operating procedures, and lead to efficiency increase as well as development of managerial policy.

The purpose of this thesis is to identify and analyze bottleneck in an underground blasting cycle in one of Boliden's mine. For that reason, methodology derived from TOC as bottleneck theory will be used to perform some mitigating and improvement steps acting toward bottleneck and performance of blasting cycle. TOC methodology will be combined

with DES. DES approach will be used as the main tool for bottleneck identification and will facilitate execution of various development aspects.

1.1 Problem statement

In mining industry bottlenecks which are commonly considered as the capacity bottlenecks influence choice of operating fleet, resources and organizational structure. Therefore, some crucial processes in the mining operations affect mine design and mine planning. However, it may turn out that the true bottlenecks are not because of capacity limitations but because of inaccurate planning or management. It is very important to identify the true bottleneck and then design a system around it. Inappropriate identification of a system's bottleneck may result in lack of managerial focus on a real problem, hence unnecessary improvements might be implemented in inaccurate places. To increase efficiency in mining operations and improve production it is critical to manage bottlenecks accurately and find simple solutions for system's improvements.

Boliden Mineral AB has started working in Kristineberg mine on a TOC approach. Preliminary study included some changes in organization structure which concerned division of fleet operators so they could focus only on one type of operations instead of handling different types of machines. Also, KPI system was implemented to control the progress of mining activities. However, for thesis case TOC is related to blasting operations and its organization procedures.

In Kristineberg mine, especially in underground operations there might be constraints which limit production. The production rates are expressed in tons which are dependent on number of performed blasts. Blasting cycle includes several complex activities. This study is addressed to investigate underground blast cycle operations and its limitations. Once the constraints of the system are known, it will be easier for both planning managers and engineers to focus on necessary areas and further improvements implementation.

1.2 Research objectives

The primary goal of this thesis is to identify and analyze bottleneck in an underground blast cycle operation. This objective will be achieved by analysis of processes, utilization of resources and operations planning. During bottleneck identification and analysis,

simulation approach and TOC concept will be used and assessed. This research includes following objectives:

- Bottleneck identification study among industries
- Bottleneck identification study in mining industry
- Use of simulation for bottleneck identification
- Propose suggestions and solutions for bottleneck improvement
- Indicate potential of improvements for constrained operations
- Assess applicability of TOC in mining operations

1.3 Research questions

During the thesis work author will answer the following research questions which are associated with the main goal:

- How to properly identify bottlenecks in underground mining operations with available techniques?
- How combination of TOC and simulation can improve mining processes and influence production planning?

1.4 Methodology

A methodology that will be used for the purpose of this master's thesis will be primarily based on computer simulation studies with use of particular simulation software. Simulation software SimMine will be used because this software is fully focused on mining operations, and during thesis work a license of this software was provided by the company. This approach will allow to model different scenarios of operations and will provide faster results for their further analysis. Additionally, main principles of TOC will be used for problem examination and search for improvements. Methodology taken from TOC will support the thinking processes during problem analysis and will allow to look at issues from different views. These two approaches will be combined.

1.5 Mining in Boliden

Boliden Mineral AB is a mining company which started its operations with the first gold discovery in the 1920s. Boliden has been involved in mining for more than 90 years and it has become the world class mining company in terms of productivity through technological development. Boliden operations include mining, smelting, and recycling. Mining operations are mainly focused on base metals like copper, zinc, lead, and nickel, but also gold and silver are significant in production planning and mining strategy. Boliden operates its mines in Sweden, Finland, and Ireland, in both underground and open-cast mining. Smelters are situated in Sweden, Norway, and Finland.

Boliden is among world's top five zinc producers and is very significant copper producer in Europe. Boliden's total production of metals in concentrate exceeded 500 kilotons and its total revenue was more than 40 billion SEK for 2016FY (Boliden, 2016).

In Sweden, Boliden Mineral AB operates mines in Garpenberg, Boliden Area, and Aitik. In Boliden Area, company owns and operates mines which are situated in the Skellefte field. This area includes Renström, Kristineberg, and Kankberg underground mines and Mauriliden open-cast mine. Kristineberg mine will be described in the following chapters as its operations are included in the scope of these thesis.

1.5.1 Underground mining

Underground mining consists of many complex processes and operations which main objective is to exploit the orebody in efficient and safe manner. In Kristineberg the access to the underground mine is facilitated by the main ramp. From the main ramp, numerous drifts are spreading out in several directions to reach different sections and parts of the orebody. Development of drifts and stopes is performed with conventional techniques, with the use of blasting materials. Blasted ore is transported to the primary crushing station and afterwards it is hoisted by the skip to the surface. Figure 1 presents an overview of underground mining in Kristineberg mine.

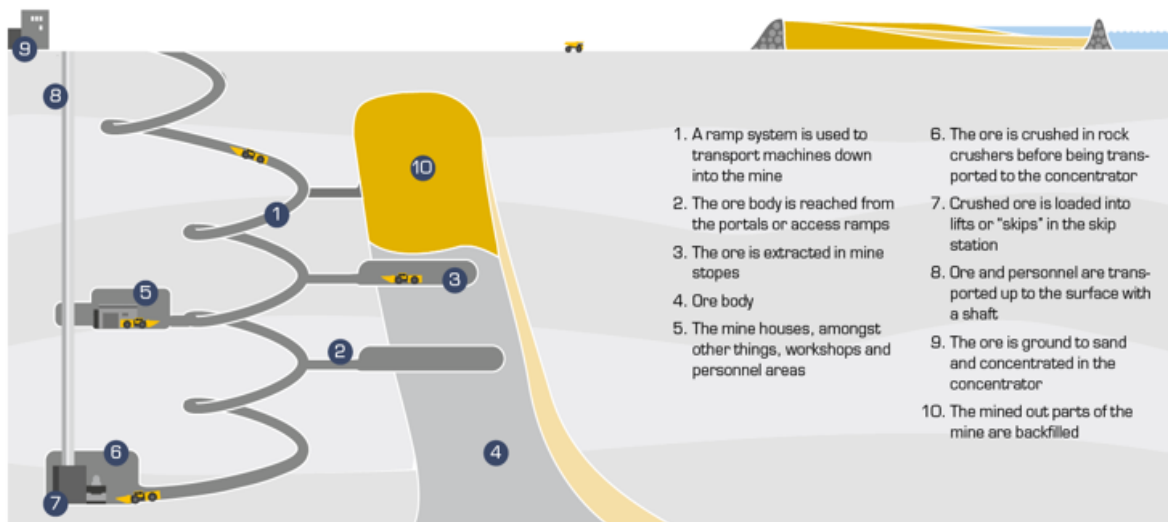


Figure 1 Underground mine – overview (Boliden, 2016)

1.5.2 Blasting cycle operations

In Kristineberg mine development and ore extraction are based on conventional methods. Complete blasting cycle consist of 12 continuous phases. Figure 2 presents a full blasting cycle with its activities. As it is depicted in Figure 2, the blasting cycle commences with drilling. The face which is prepared to be blasted is drilled by drilling jumbos in accordance with the production plan. The exact number of boreholes is required to meet production demand from one blasting.

After drilling, the boreholes are charged with explosives and blasting caps are installed. The blasting is executed by remote firing system. During blasting phase, all staff must be outside blasting areas, and be in safe zones like canteen. After blasting has been completed, a ventilation is launched in order to remove dangerous post-blasting gases and dust. Ventilation facilitates good working conditions for workers and supply them with fresh air. Subsequently, the blasted material is sprinkled with water to depress dust during loading operation.

The next step in the cycle is to muck out the blasted ore and load it onto the transportation truck. The loading is performed by front end loaders and then ore is transported to the crushing station.

After blasted material has been mucked out and transported, the scaling phase is carried out. Scaling operation is performed in order to secure the face and to prevent loose rock in walls and roof from falling down. Afterwards, scaled rock fragments are removed in the primary cleaning operation. Smaller rock fragments undergo fine cleaning.

Following the scaling, shotcreting phase is performed. The reason for shotcreting is to reinforce the roof and the walls. Shotcreting operation is completed when the concrete is dried and well bind with the rock surface.

After shotcreting, a bolting operation is carried out. Bolting is performed to reinforce the roof and the walls. Bolting involves two phases. The first phase is drilling and the second phase is bolting, where rock-bolts are installed. There are two types of bolting that are applied in the mine. It is cement and resin bolting.

The last operations which are performed before the next blasting round may commence are face scaling and face cleaning. Face scaling and cleaning prepares mining face for accurate and efficient drilling in consecutive cycle.

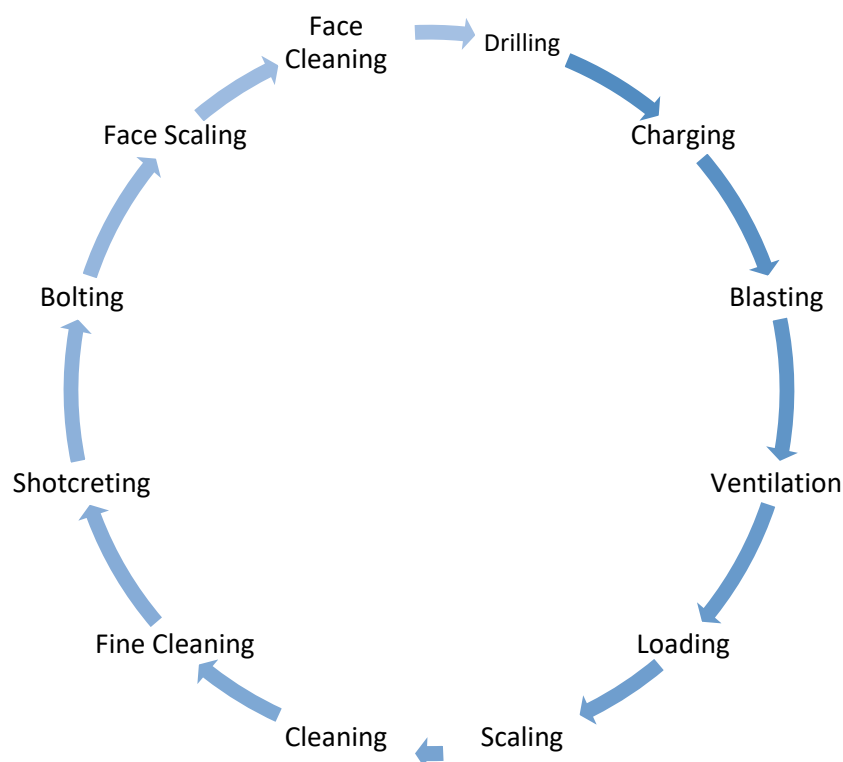


Figure 2 Blasting cycle operations (Boliden, 2016)

2 Literature study

This chapter includes review of literature and studies regarding bottleneck. Additionally, descriptions of bottleneck identification methods are presented. This chapter provides an overview of terminology regarding bottleneck problems.

2.1 Bottleneck theory

Unproductive and ineffective processes in the systems are mainly caused by bottlenecks. Significant advance in production managed by appropriate utilization of available resources, throughput increment, and minimization of production costs may be achieved by immediate and exact identification of bottlenecks (Li et al., 2009). Nevertheless, not all of existing methods of bottlenecks detection can be valuable for particular case. Some of the methods may just not find its applicability due to system complexity or datedness. According to Yan et al. (2010), a classical way of bottlenecks detection can be ambiguous and challenging (Yan et al., 2010).

2.1.1 Definition and origin of bottlenecks

Bottleneck definitions varies among different industries due to organizational and operating viewpoint. Shen (2010) states that “[...] using different bottleneck definition will identify different bottlenecks even in the same production system”. Consequently, the definition of a bottleneck is not uniform by academic description (Shen and Chen 2010).

Goldratt and Cox (1986) describe the first-time concept of a bottleneck in the book *The Goal*. According to Goldratt and Cox (1986) a bottleneck is defined as “any resource whose capacity is equal to or less than the demand placed upon it”. Additionally, a countertype to the bottleneck is a non-bottleneck resource, and is defined as “any resource whose capacity is greater than the demand placed on it” (Goldratt and Cox, 1986).

In serial production lines comprised of sets of machines, a decrease of the system production rate is often caused by the machine with the lowest production rate. This machine is considered as a bottleneck (Chiang et al., 1999). Closely related definition of a bottleneck is given by Zhai et al. (2011). He describes a bottleneck as a process which constrains the system’s performance. However, in the literature there are also different

definitions of bottlenecks. Lawrence and Buss (1995) assign three definitions to bottlenecks: short-term, inventory, and production, accordingly.

1) Short-term:

In the long-time perspective, demand is constrained by the capacity, and thus reduction of demand rate may result in loss of a business. However, in the short-term perspective demand can exceed capacity and for that reason bottleneck mitigation techniques must be applied.

2) Inventory:

This definition takes into account levels of work-in-process (WIP) inventories. A resource is considered to be a bottleneck if it has the largest WIP.

3) Production:

In long-range planning, resources which highly limit the throughput or output are considered to be bottlenecks. In this case the most practical measure to identify such bottlenecks is capacity utilization.

Goldratt and Cox (1986) underline that in nearly every production system exist at least one bottleneck, however, the most important aspect which is pointed out as a method to a great success is the bottleneck management.

Despite the fact, that there is no general agreement on the bottleneck definition, it is well-known and accepted that the bottleneck identification is a critical undertaking in the interest of throughput increase. Throughput is a substantial factor which influences production performance, therefore, throughput analysis is of the highest importance for control and management. Appropriately identified bottleneck facilitates its management. Consequently, increasing the bottleneck's efficiency will cause the growth of the overall system efficiency (Kahraman, 2015).

Various factors of a system have an influence on its functionality and performance. Factors like machine utilization and capacity, work organization or number of skilled operators may contribute to bottleneck formation (Wang et al. 2005). According to Petersen et al. (2014) the main reasons for bottlenecks in the systems are:

- Planning problems
- Incompetence of personnel

- Technical reliance
- Lack of system development

2.1.2 Types of bottlenecks

Different definitions of bottleneck lead to various divisions of bottleneck types (Kahraman, 2015). Bottleneck types differ from each other when considering production industries. In accordance with Lima et al. (2008), there are three main types of bottleneck, which can be classified as the following:

1) Simple type bottleneck:

During the whole time of system functioning, there is only one bottleneck machine.

2) Multiple type bottleneck:

During the whole time of system functioning, there are some bottlenecks and they are permanent.

3) Shifting type bottleneck:

During the whole time of system functioning there is no single bottleneck. The bottleneck shifts between different working stations as the process proceeds.

Classification of bottleneck types presented by Lima et al. (2008) is widely acceptable. However, Roser et al. (2002) categorizes bottlenecks into average or momentary types. Average bottleneck in the system is present over the whole-time period, whereas a momentary bottleneck exists only at a specific time frame (Roser et al., 2002).

Furthermore, some bottlenecks may have a tendency to repeat over some period of time (Kahraman, 2015). Bottlenecks which can appear at the same place and in nearly the same time interval are described as recurring bottlenecks (Chen et al., 2004). Wang et al. (2005) state that: "Some bottlenecks may appear temporarily and some may remain static."

Wang et al. (2005) classify bottlenecks differently. He divides bottlenecks into two categories:

- 1) Bottlenecks based on the system performance, where measurements concerning utilization and average waiting time are highly important.
- 2) Bottlenecks based on the system sensitivity, where performance and throughput of the system is analyzed on machines parameters.

Since every production system is evaluated on its efficiency and profitability, costs and revenues of these systems are continually considered. In these case resources that contribute to lower profitability of a system are identified as bottlenecks. Lawrence and Buss (1995) name these resources as “economic bottlenecks”.

2.2 Methods for bottleneck detection

Bottleneck detection procedure is closely connected with throughput analysis. Throughput is a crucial parameter when it comes to evaluation of production performance. Moreover, throughput analysis is the most significant aspect for the design, supervision, and management of production systems. In order to increase the system’s throughput, a bottleneck must be detected. Commonly, bottleneck detection methods can be classified as analytical methods and detection based on computer simulations. Analytical methods have been widely used in industries with long production lines and to identify long-term bottlenecks, whereas computer simulation methods are intended for more complex systems. Simulation methods are often based on discrete event simulation (DES) (Li et al., 2007).

Wang et al. (2005) gathered and summarized bottleneck detection methods, what is depicted in Table 1. However, computer simulation may be used to validate most of those methods (Kahraman, 2015).

Table 1 Bottleneck detection methods; redrawn after (Wang et al., 2005)

Performance Based Detection Methods	Shift Bottlenecks Detection Method	Sensitivity Based Detection Method
<i>Measuring Average Waiting Time:</i> Law and Kelton, 1991 Pollet, et.al, 2000	Roser, et.al, 2002a Roser, et.al, 2002b Roser, et.al, 2002 Roser, et.al, 2003	Kuo, et.al, 1995 Chiang, et.al, 1998 Chiang, et.al, 1999 Chiang, Kuo, Meekov, 2000
<i>Measuring Average Workload:</i> Law and Kelton, 1991 Berger, et.al, 1999	-	-
<i>Measuring the Average Active Duration:</i> Roser, et.al, 2001 Roser, et.al, 2003	-	-

2.2.1 Average waiting time measurement

This approach involves measurement of average waiting time of a resource and focuses on recognition the machine which has the longest waiting time. The machine with the longest waiting time is considered to be the bottleneck. This method also holds the idea of the queue length as well as similar average per-hop delay measurements. Mentioned measurements find application in systems which contain limited buffers and are only considered for machines' analyses (Wang et al., 2005).

2.2.2 Average workload measurement

Workload measurement method may be useful in bottleneck detection. Within this approach the machine which has the highest utilization rate (workload) is recognized as the system's bottleneck. However, this method may cause some uncertainties when there are two or more machines being active and have similar workload rate. These uncertainties and errors can result from random data variations. Therefore, a bottleneck probability matrix has to be designed in order to give the best result for exact bottleneck detection. This method may be complicated when investigating large systems (Want et al., 2005).

2.2.3 Average active duration measurement

The following method was proposed by Roser et al. (2001). Within this concept, a machine or any other resource has two states. The state can be either active or inactive (Table 2). The machine which is working, and has the longest average active duration time is recognized as the bottleneck (Roser et al. 2001). Activities such as repairs and service improvements are included in the machine's active state, and act toward system's throughput. Average active duration method supported by computer simulation results can detect the bottleneck more precisely. Additional advantage of this approach is uncomplicated application and possibility of being used in automated guided vehicles systems (Wang et al., 2005).

Table 2 States of machines and resources (Roser et al., 2001)

Machine	Active	Inactive
Processing Machine	Working, in repair, changing tools, serviced	Waiting for part, waiting for service, blocked
AGV	Moving to a pickup location, moving to a drop off location, recharging, repair	Waiting, moving to a waiting area
People	Working, scheduled break	Waiting
Supply	Obtaining new part	Blocked
Output	Removing a part from the system	Waiting
Computer	Calculating	Idle

In addition to Roser (2001), Tamilselvan (2010) proposed a simulation procedure for active duration bottleneck detection, what is shown in Figure 3. The machine is considered to be a momentary bottleneck if its active state is the longest at any instant. Additionally, the machine with the longest average activity time is considered to be the average bottleneck machine.

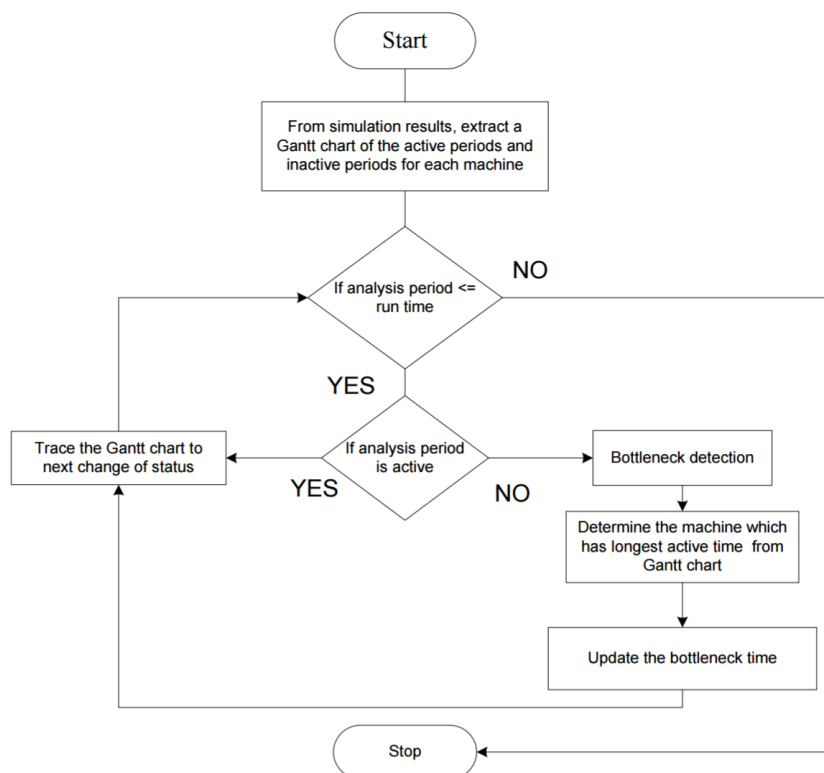


Figure 3 Active duration method (Tamilselvan, 2010)

2.2.4 Shifting bottleneck detection

Shifting bottleneck detection method is based on active duration measurements. This method focuses on recognition the machine or AGV with the longest active duration time, and consequently identifies this resources as the bottlenecks. Furthermore, the bottlenecks are categorized as sole bottlenecks and shifting bottlenecks. Active working time of shifting bottlenecks overlaps with the following bottleneck, whereas sole bottlenecks do not overlap with previous or following bottlenecks. Calculation of the percentage of the time when a machine is sole or shifting bottleneck may help to determine the probability of the machine to be the bottleneck. Shifting bottleneck detection method works accurately for both AGV and non-AGV systems. This approach also correctly detects sensitivity based bottlenecks supported by simulation results and verification (Wang et al., 2005). Figure 4 illustrates the example of sole and shifting bottlenecks.

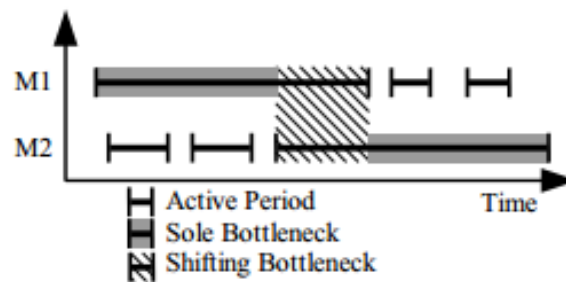


Figure 4 Shifting bottlenecks (Wang et al., 2005)

2.2.5 Throughput-based method

Throughput-based method uses simulation in order to identify system's bottlenecks. Firstly, it is necessary to identify the target throughput of the system. Then, the following steps focus on measurements and comparison of the throughput whenever any new resource is added to the system until all of the resources are placed in the system. Every time the new resource is added to the system, a simulation is performed to analyze the throughput. The resource which is responsible for the largest throughput reduction is considered to be the bottleneck. However, a simulation configuration is needed to be done every time a new resource is added, hence the computational time of the system might be

very long (Kahraman, 2015). According to Almansouri (2014), simulation set-ups might make it difficult to implement this methodology if dynamic resources are involved.

2.2.6 Turning point method

This method analyzes the bottleneck resources (Figure 5) by identification of the machine which contributes to blocking the upstream resources and makes downstream resources to be waiting for work (idle time; starvation). As a result of analysis, the busiest resource in the production line is considered to be the bottleneck (Almansouri 2014). Within this method and with the use of online data it is possible to identify short-term and long-term bottlenecks. Long term bottlenecks are important for process planning whereas short term bottlenecks are beneficial to process management (Kahraman, 2015). Moreover, supported by simulation run data or real-time observations, this method facilitates quick bottleneck detection, because it is focused on starvation and blockage time (Almansouri, 2014).

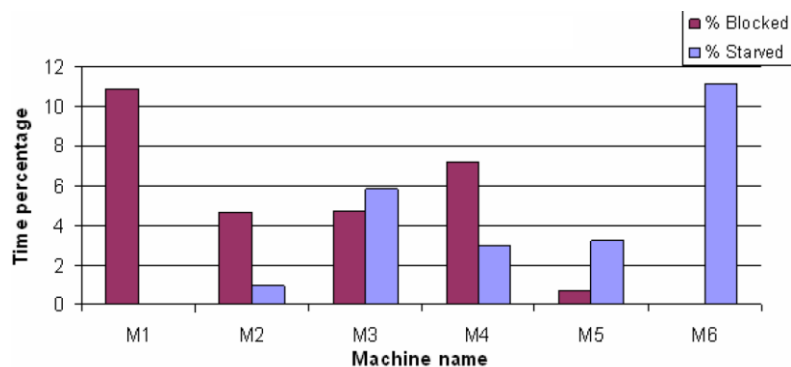


Figure 5 Blockage and starvation times (Li et al., 2009)

2.2.7 Inactive duration method

This approach is similar to certain point to the turning point method because indicates which machines are blocked and which are idle. According to Kahraman (2015) this method identifies short-term, average, and shifting bottlenecks in the systems with or without buffers. As in other bottleneck detection methods, simulation is also used here to track the characteristics of bottleneck machines and resources. Simulation results are used to

identify the inactive systems in both upstream and downstream processes. Furthermore, a bottleneck chart is created. This chart visualizes bottleneck times of analyzed machines (Tamilselvan, 2010). Figure 6 demonstrates the simulation procedure for the inactive duration method.

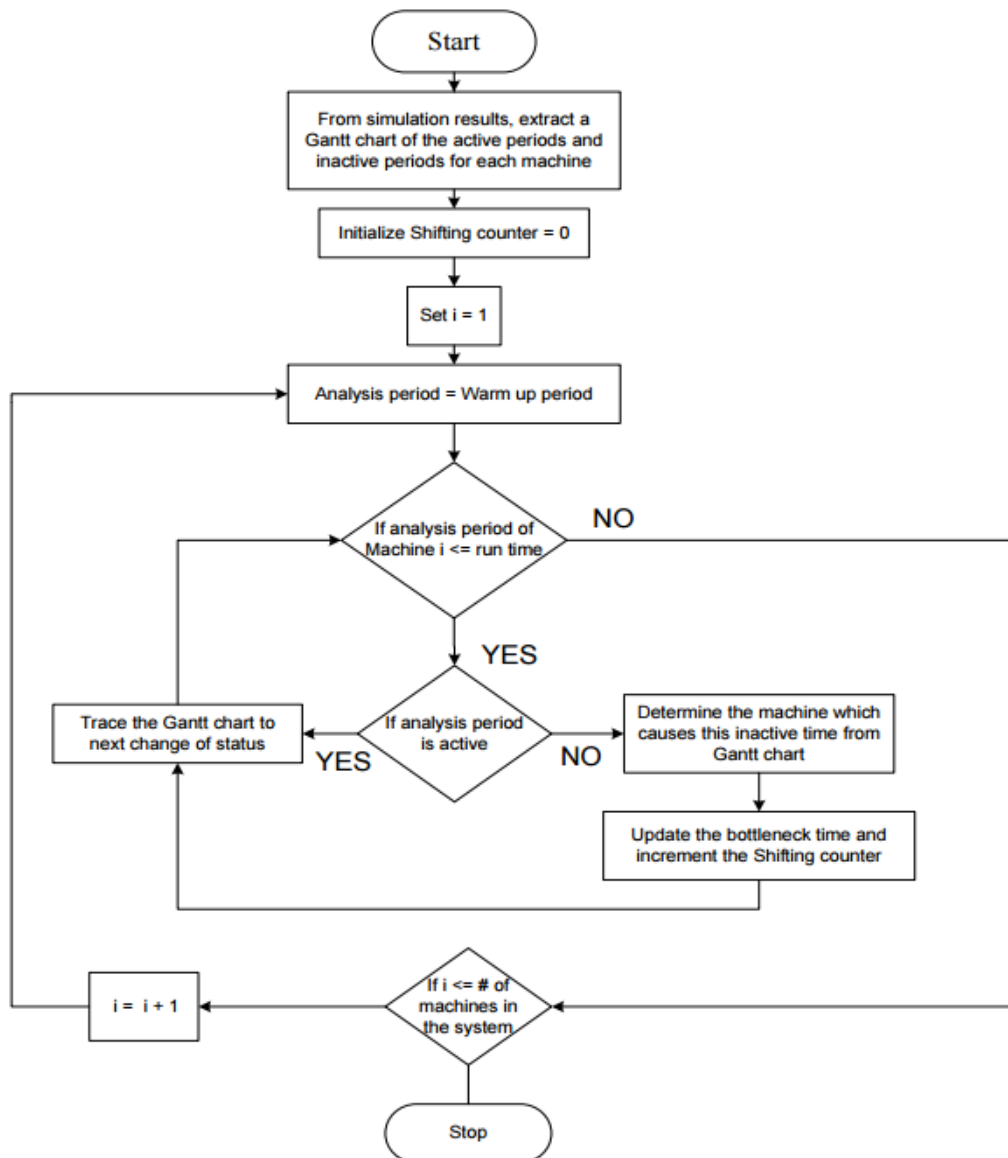


Figure 6 Flowchart of inactive duration method (Tamilselvan, 2010)

2.2.8 Simulation method

Simulation method is intended for measurement and analysis of system's performance. Simulation is an imitation of a real system and with proper analytical approach and model understanding it gives results that may help in system analysis (Almansouri, 2014). Many industries have used simulation to identify systems' drawbacks and reasons for underperformance. It has become very useful and commonly used in bottleneck identification (Kahraman, 2015).

Even though a simulation does not define exact solution of a problem, this approach is very useful in calculation of extreme values. In contrast to analytical methods, simulation approach is crucial when computing complex systems with numerous numbers of resources, performance measures, and combined and interdependent operations. Additionally, simulation is used to manage vast systems, especially when representation of input data variables is nonlinear and includes some randomness. Simulation is very popular among various operating activities and undertakings as a method for bottleneck detection (Kahraman, 2015).

On the other hand, simulation has some disadvantages when compared to analytical methods. One of them is building of a simulation model which is highly time consuming. Furthermore, simulation may not give the best solution to a problem, but presents numbers and values that subsequently should be analyzed. Simulation approach is based on assumptions and provides estimated results, thus, misinterpretation and misunderstanding during analysis may occur. It is very important to accurately examine the input data, because the results are highly dependable on data quality (Kahraman, 2015).

When performing a simulation, a bottleneck may be easily detected, however, it is very important to thoroughly and deeply investigate the input data, output results, as well as analyze the interdependencies within the system components.

2.2.9 Inter-departure time measurement:

This method focuses on measurements of inter-departure time data of machines over a certain period. The machines' states are defined as busy, idle, blocked, and fail. The resource which has the lowest idle and blocked state is considered as being the bottleneck.

Using this rule, the next resources would be considered as the secondary bottleneck (Almansouri, 2014). Kahraman (2015) states that the bottleneck will influence other resources in the system, not being influenced but other resources itself.

2.2.10 Theory of constraints

This paragraph will focus on overview of theory of constraints (TOC) as a methodology for bottleneck identification, management and possible mitigation approach. Subsequent paragraphs will assess the TOC applicability for an underground blasting cycle as one of the solutions for bottleneck improvements.

TOC is one of ongoing improvement methodology and is a common approach for overall system control and production scheduling (Kasemset, 2011). TOC evolved from Optimized Production Timetables (OPT) concept as a tool for performance management, production and logistics. OPT initially faced some difficulties in implementations. OPT was continuously improved in the production systems and eventually, after numerous upgrades and advancements it encompassed every aspect of business. The final concept was introduced as TOC in 1987 by Eliyahu Goldratt (Rahman, 2002). According to Goldratt (1988), a TOC is stated as: “an overall theory for running an organization” (Goldratt, 1988).

The TOC consists of two main components. First component is a philosophy that underscores the principles of TOC and is commonly described as TOC’s “logistics paradigm”. This “logistics paradigm” includes five-focusing steps, the drum-buffer-rope (DBR) scheduling methodology, and buffer management technique. The first component and its approach suggests that the main constraint (bottleneck) of the system may be related to management policy instead of being a physical constraint. Therefore, in order to effectively implement the process of ongoing improvement (POOGI) and to emphasize management constraints, a second component of TOC was developed. This universal approach is the Thinking Process (TP) and is considered to have the strongest impact on industry/business improvement (Rahman, 2002).

The primary goal of TOC is to focus on system’s constraints (bottlenecks) and their accurate management in order to increase throughput (Kahraman, 2015). According to Goldratt (1994) each system has at least one component that is a system’s limiting factor (bottleneck) or capacity constraint resource (CCR). Goldratt and Cox (2000) say that the

goal of the organization is to make money through sales, and it is achievable through increasing the net profit what is equal to increase return on investment (ROI) and cash flow simultaneously. Furthermore, they indicate three measures to achieve the goal:

- 1) Throughput: "Is the rate at which the system generates money through sales."
- 2) Inventory: "Is all the money that the system has invested in purchasing things which it intends to sell."
- 3) Operating expense: "Is all the money that the system spends in order to turn inventory into throughput."

The aim is to increase throughput and to decrease inventory and operating expense (Goldratt and Cox, 2000).

2.2.10.1 TOC's philosophy

In order to identify and optimize the system bottleneck(s), Goldratt and Cox (2000) presented five focusing steps approach. Five focusing steps (see Figure 7) are a part of a continuous improvement process. Rahman (2002) summarized this approach as follows:

- 1) **Identify the system's bottleneck(s).** The bottleneck may be caused by physical resources (people, machines, supplies, materials) or management. The most important task is the identification of bottlenecks and subsequent prioritization from the highest to the lowest impact on the organization.
- 2) **Exploit the system's bottleneck(s).** Decision should be made on the bottleneck type. Physical bottlenecks should be run and exploited to the utmost possibilities and effectiveness. If bottleneck is within management, then the policy should be replaced by a new one which supports throughput increase.
- 3) **Subordinate everything else to the bottleneck(s).** Bottleneck(s) control and dictate the production throughput. Therefore, any other resource or element which is non-bottleneck should be subordinated to the bottleneck and synchronized with it in order to increase the bottleneck effectiveness. Synchronization of resources will act toward more effective utilization.
- 4) **Elevate the system's bottleneck(s).** If bottleneck(s) still exist and highly impede the system, it is necessary to implement strict bottleneck improvements to improve its effectiveness and performance. Improving the performance of the bottleneck will

simultaneously increase the effectiveness of non-bottleneck resources. This will result in the whole system performance improvement; however, a new bottleneck may appear.

- 5) **If the constraint has been broken, go back to step 1 but prevent inertia from becoming the system's bottleneck.** As the environment of the organizational operations changes, some improvements in the system may not provide a long-standing effect. TOC as a process of ongoing improvement implies that a management policy should adapt to a new system situation.

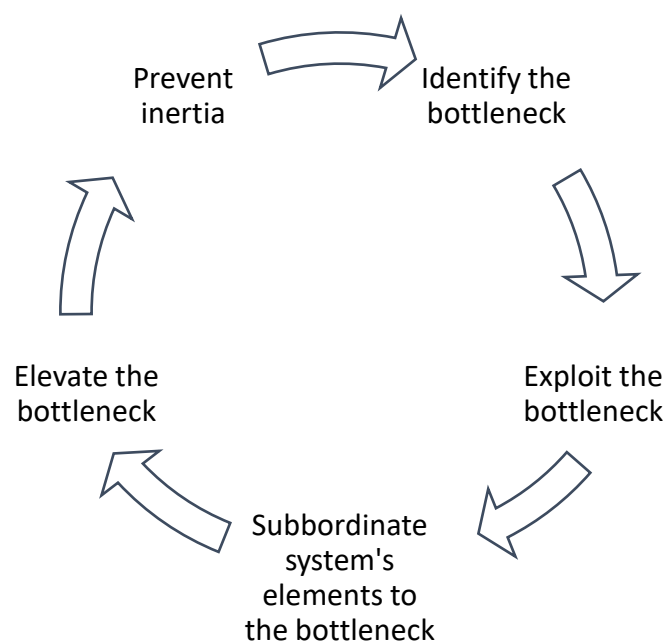


Figure 7 Five focusing steps

2.2.10.2 Drum-Buffer-Rope technique

Drum-Buffer-Rope (DBR) presented in Figure 8, is included in the logistics paradigm. According to Goldratt and Fox (1986) DBR is a method which helps to protect the total throughput of the system. To protect the throughput which is determined by the bottleneck, DBR uses buffers. Buffers are time- or stock-related and are responsible for protecting the production schedule. The bottleneck is defined as the system's drum because it sets the pace of the flow, thus it is considered as the production schedule. To exploit the bottleneck constantly and to make sure it is always busy, a buffer should be placed in front of the bottleneck. In order to synchronize and subordinate upstream as well

as downstream process to the bottleneck a rope is used in the system (Pandit et al., 2012). Kahraman (2015) states that: “The rope is the demand for the new material needed for the system”. Pandit et al. (2012) comments that the DBR has the following assumptions:

- 1) It is necessary to develop a master production schedule which will be connected with the system’s bottleneck (Drum).
- 2) It is crucial to protect the system’s throughput from minor disruptions by the use of time buffers at critical points (Buffer).
- 3) Every resource should be protected and subordinated to the drum pace (Rope).

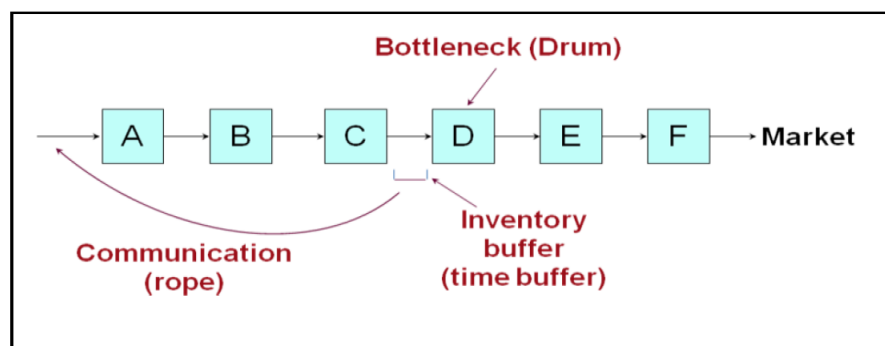


Figure 8 Drum-Buffer-Rope method (Pandit et al., 2012)

2.2.10.3 Thinking Process

Thinking process (TP) described by Rahman (2002) is a logical tool of TOC and is used by managers during the work on the bottlenecks. TP supports problem analysis and resolution. This decision-making approach includes three generic decisions (Rahman, 2002):

- 1) Decide what to change.
- 2) Decide what to change to.
- 3) Decide how to cause the change.

In order to address these questions, a cause-and-effect diagrams are formed. The diagrams present a system logic and interdependencies between subsequent steps, and emphasize obstacles and disruptions which occur within the system. The break-down structure of cause-and-effect points helps to answer generic questions (Rahman, 2002). Table 3 summarizes generic questions, purposes and tools. Since some of the core problems

in industries are imbedded in the management, bottlenecks are possible to arise. TP methodology supports organizations by underscoring management constraints and facilitates solving problems that impede production goals.

Table 3 TP tools and their function (Rahman, 2002)

Question	Purpose	TP tool
What to change?	To identify core problem	Current Reality Tree (CRT)
What to change to?	To develop simple and practical solutions	Evaporative Cloud (EC) Future Reality Tree (FRT)
How to cause the change?	To implement solutions	Prerequisite Tree (PRT) Transition Tree (TT)

2.2.11 TOC in the Mining Industry

TOC methodology has become very popular among manufacturing industries since 1986. TOC has been very successful in application in plants which include several production and assembly lines. However, TOC approach has not been popularized among mining industries. There are several studies and papers which describe and assess the applicability of this methodology in mining.

In mining operations bottlenecks may appear in different processes, and they can move between different operations regularly or irregularly. The buffer sizes may be very large in comparison to plant production lines, and mining operations might be constrained by different factors, thus operation ratio may easily fluctuate (Kahraman, 2015). Mining operations and mining production have probabilistic nature due to possible constraints and uncertainties. According to Ray et al. (2010) TOC concept is the most suitable for deterministic situations, therefore, probabilistic situations need further investigation and evaluation.

Baafi et al. (2010) used TOC methodology in the pillar development cycle of an underground coal mine. In his study, he describes the production cycle where continuous miner, a roof bolter, and a shuttle care are utilized. The study compares different scenarios of machines selection and their performance ratio. Baafi et al. (2010) concludes that TOC methodology

can be systematically implemented in coal mine development cycle, however, it lacks accurate analytical tools for performance analysis. To suffice this drawback a DES models are combined with TOC approach.

Phillis and Gumede (2009) investigated stoping operations in underground mining, and focused on shifting procedure. Their study involved application of Critical Chain Project Management (CCPM) methodology, which is one of TOC's project management approach. The study indicated that it is possible to implement changes in mine planning and execution, what was proved with advantageous results of shift's time utilization and shift's team performance.

Heerden (2015) combines TOC's principles and tools with operating time measurements of machines in underground coal mine. He investigates continuous miner and shuttle car in order to identify a CCR in production cycle. His study underscores the bottleneck causes and suggests possible solutions for CCR.

According to Kahraman (2015), Bloss (2009) used TOC methodology to identify bottleneck in underground mine operations and subsequently debottleneck them. He managed to obtain an eighteen percent throughput increase. Furthermore, Bloss (2009) used buffers in downstream and upstream processes and focused on comparison of capacities in order to identify bottleneck.

3 Simulation methodology

This chapter describes theory and methodology which stands behind computer simulation. The most important facts and components of simulation approach will be presented and described in the following subsections.

3.1 Simulation theory

According to Banks (2000), simulation imitates actions, operations and behaviors of a real-world processes or systems over time. Simulation creates an artificial history of the system, and subsequent measurement of that artificial history is used to present interpretations regarding the operating attributes of the real system that is represented.

Simulation approach is essential methodology for problem solving that help to find solutions of numerous real-world problems and issues. Simulation may be used for description and further analysis of system's nature and its performance. With simulation, it is possible to ask "what if" questions concerning the actual system, and support design of the real systems. Furthermore, simulation facilitates modelling of existing and conceptual systems (Banks, 2000).

Cochrane (1998) states that: "Computer simulation is a tool that is commonly used in operations research to study the way in which a system works, and to look for ways in which the system can be improved".

Simulations have become very popular among different industries and many companies derive benefits from its advantages. A reason for that is the possibility of testing different scenarios and analyzing phenomena which occur in the system without allocating new resources or making huge investments. Simulation allows to compress or expand the time of simulation study. This allows to investigate thoroughly all the activities and phenomena within hours, whereas in real world this study will be longer and more demanding (Banks, 2000).

According to Banks (2000), computer simulation especially DES is based on several concepts. These concepts include the following components:

- Model – is a representation of an actual system. Model should be complex in order to answer questions which were asked during simulation.
- Events – are occurrences which change the state of the system. Events can be internal (which happen in the simulation) or external (happen out of the simulation).
- State variables – are collection of all necessary information which help to describe to sufficient extent the changes which occur within the system at certain point in time.
- Entities and attributes – entities are objects in the system, which are static or dynamic, and have attributes describing their features.
- Resources – are entities which service dynamic entities. Resource can service simultaneously one or more dynamic entities.
- Processing list – is a representation of entities which are attached to service resources. Lists may be processed as FIFO (first-in-first-out) or LIFO (last-in-first-out).
- Activities and delays – activity represents a duration of time, where duration can be constant, input from a file or a random value based on statistical distribution. A delay represents an unknown duration which is caused by any disturbance in the system.

DES models include activities which cause time to advance. Majority of DES models also include delays because entities which are present within the model are waiting for their resources. Each event is described as the beginning and ending of a particular activity or delay (Banks, 2000).

3.1.1 Discrete event simulation

Two different methods make it possible to analyze the system of interest. One method is an experiment approach on the actual system and the second one involves a model creation which represent this system. In order to design a model of a real system, a significant set of assumptions is required that could be processed by the operating system. Assumptions which are a part of a model are about to interact with system's objects. Interaction between assumptions and objects must form certain mathematical and

logical relationship. Subsequently, these assumptions may be solved with the use of simulation, where models are computed with computer software and generate results which are analyzed in the later process (Salama, 2014).

There are two ways of simulation model classification (see Figure 9). A simulation model may be deterministic or stochastic. Deterministic model does not contain any random components. In that model, a set of input conditions is specified and then an output is determined by equations which can be simple or complex. Stochastic model can be applied to continuous or discrete activities and it has at least one random input component and analogically produced output will be also random. Therefore, the result of a stochastic model will be only an estimate of the real model characteristics (Law and Kelton, 1991).

Discrete event simulation may be used to model a system which is developing over time and which represents changes of state variables that are instantaneously changing at discrete points in time (Law and Kelton, 1991). Furthermore, simulation models may be classified as static or dynamic. Static model represents a system at a specific time, whereas dynamic model represents a system as it develops over time. Monte Carlo simulation technique is used in computation and evaluation of static models (Salama, 2014). Salama (2014) states that: “Discrete event simulation applies different types of rules and procedures that increase understanding of the interaction between variables and their importance in the system performance” (Salama, 2014).

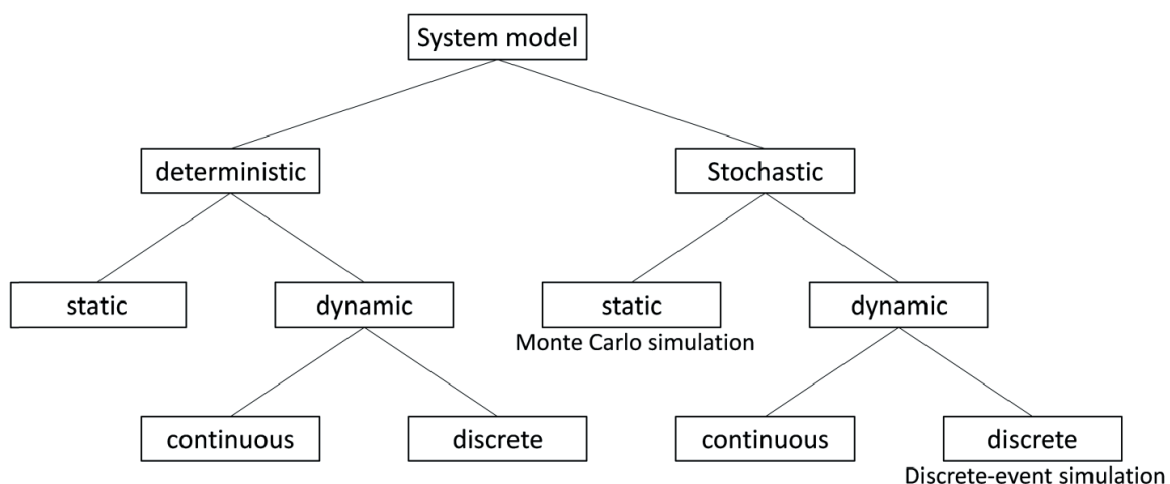


Figure 9 Classification of system models (Salama, 2014)

Discrete event simulation enables to imitate dynamic and probabilistic nature of real world operations. Mining operations are definitely one of this type where DES finds its applicability.

3.2 Simulation in the mining industry

Mining industry has started using computer simulation since 1960s in order to simulate different operating problems (Salama, 2014). Computer simulation does not always provide an exact answer but gives a strong support when making critical decisions during system analysis. Simulation modeling is used in various mining processes when searching for optimization, improvements, or scheduling and planning.

Analytical methods are not sufficient in some particular mining systems, because of their magnitude and complexity. Therefore, simulation modeling may be easily applied. In the mining industry simulation has been used for different reasons. The following examples are:

- Train transportation system for an underground mine (Salama, 2014)
- Truck-shovel combination in Ingwe Douglas Piller (Turner, 1999)
- Discrete Event Simulation of continuous mining systems in multi-layer lignite deposits (Michalakopoulos, 2014)
- Optimization of truck-loader haulage system in and underground mine (Salama, 2014)
- Development of ore handling processes in Port Hedland (Busu and Baafi, 1999)
- Truck dispatching computer simulation in Aitik open pit mine (Forsman, Ronnkvist & Vagenas, 1993)
- Autonomous vs Manual haulage trucks (Parreira & Meech, 2010)

Some other examples of use of simulation in mining (from Fjellström, 2011):

- Maintenance scheduling for production and ground handling systems
- Dispatch control in open cast mines
- Truck utilization and operation costs in underground transportation system
- Benchmarking of operations in surface mining
- Fleet performance optimization and equipment selection

Many papers and simulation related research have proved that computer simulation modeling finds its applicability in mining industry and is useful for mine design, mine planning, equipment selection, fleet optimization and combination of transportation systems as well as production control and design.

3.3 Simulation tools and software

Computer simulation has become very popular not only within mining industry but also in any other business where processes are complex, design is robust and there is a significant demand for cost estimation and projection of activities. Along with computer simulation, many new tools and software packages were developed. Some of simulation software specialize only in one type of operations whereas others are universal and may be used in numerous activities and processes.

There are three categories of tools which are used especially in discrete event simulation. General purpose programming language, which includes FORTRAN, Java, C and C++ is the first group of tools. This group requires high programming skills, but is very flexible. The second group consists of simulation programming languages like GPSS/H, SIMAN, and AutoMod. These languages are object-oriented, have high flexibility and also require good programming skills. The third group is simulation language environment. Simulation language environment may be applied in many processes. Simulation programs in this category need very little coding and they have some in-built modeling elements and graphics. This category may include simulation software like SIMUL8, SLAM, and SimMine (Salama, 2014).

In mining operations, the following simulation software finds its applicability:

- Arena – this simulation software is applicable in various areas, such as call centers, processing, forestry, and logistics.
- AutoMod – the main focus of simulation is production and logistics system, but because of flexible environment many different processes may be simulated.
- SIMUL8 – a software provides wide range of features and options for different purposes like fleet size, resources management, and scheduling.
- SimMine – simulation package which is solely focused on mining operations for both development and production requirements.

3.4 Simulation paradigms

Discrete event simulation is divided into three main programming styles (paradigms), which characterize the way of solving simulation problems and describe model behavior. There are activity-, event-, and process-oriented paradigms (Matloff, 2008).

3.4.1 Activity oriented paradigm

In activity oriented paradigm (Figure 10) time between events is divided into discrete time steps, where time increments are regular. In every step, the state of each event of the system is checked and updated. This process is performed continuously. It is often that during very small incremental steps nothing happens in the system, but computation carries on, what wastes computer power and extends the time of simulation (Matloff, 2008).

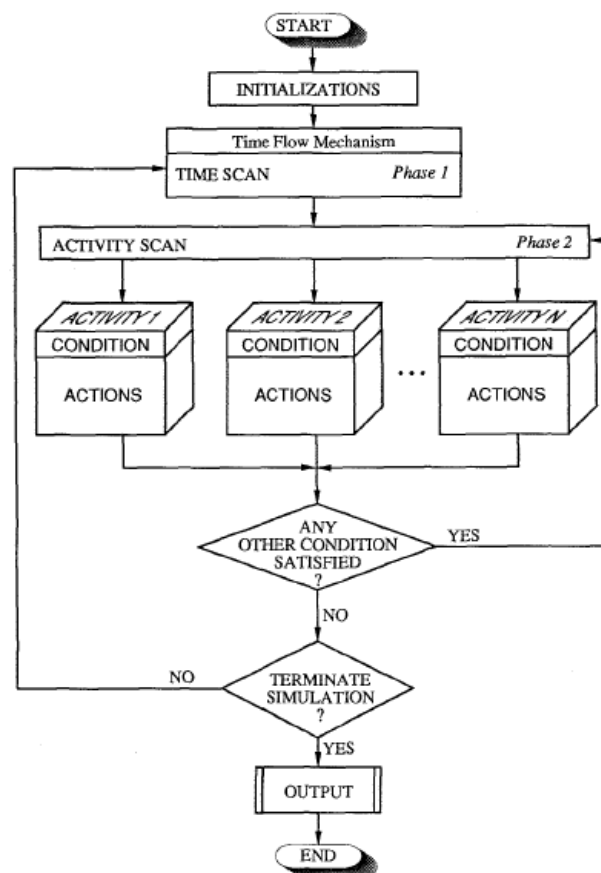


Figure 10 Activity oriented paradigm process (Balci, 1990)

3.4.2 Event oriented paradigm

In event oriented paradigm (Figure 11) all events that take place in system are listed and handled by a priority queue. The time as well as the state of system is updated when any event occurs with omission of other time steps between events where nothing happens. This type of simulation is faster than activity oriented because in the simulation process program jumps between events instead of computing every time step (Matloff, 2008).

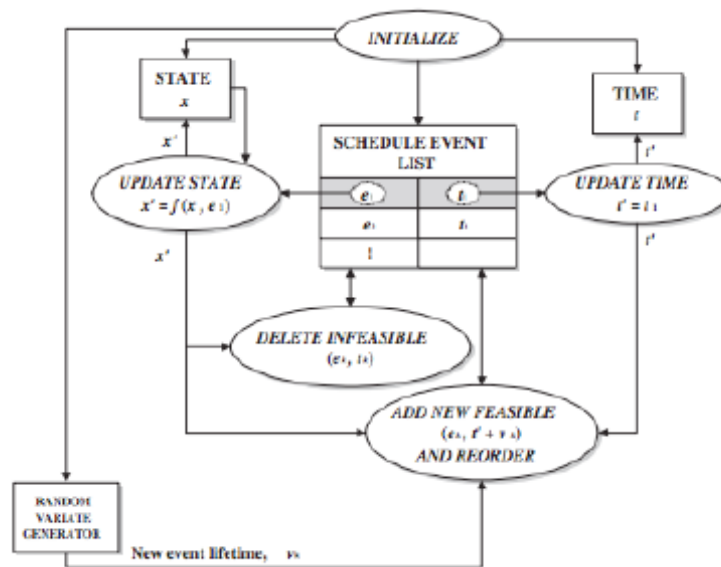


Figure 11 Event oriented paradigm process (Balci, 1990)

3.4.3 Process oriented paradigm

In process oriented paradigm (Figure 12) a system is based on entities, resources and processes. An entity (e.g. a customer or a machine) undergoes every process in the system. The processes are described as events that happen at discrete points in the system and are separated by time intervals. The system's clock is updated at clock update phase or before termination of a simulation (Matloff, 2008).

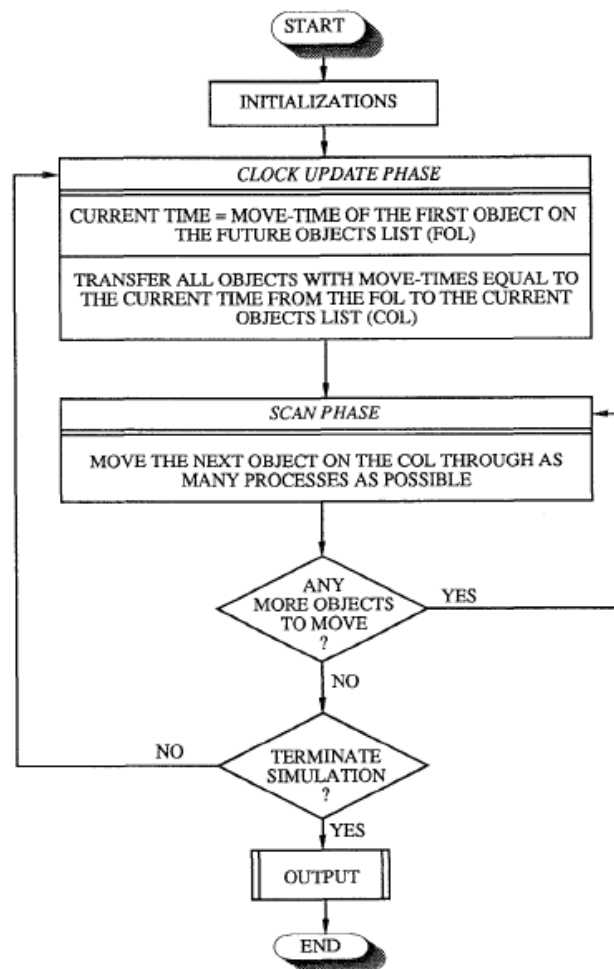


Figure 12 Process oriented paradigm procedure (Balci, 1990)

3.5 Simulation procedure

In this thesis, a discrete event simulation approach is used for problem modeling and subsequent study. The simulation model of Kristineberg mine is used for analysis of underground blasting operations. In blasting cycle, there are several activities which form a certain sequence of events that are ordered in structured way. These activities/events occur at specific time and at specific places. According to Banks (2000), a discrete event simulation enables to model and assess real systems and run them over time. The model in DES is dynamic because the system evolves and changes over time.

During simulation study a model should possess a sufficient and accurate representation of input and output data because a study itself is work with a modeled problem rather than direct work with real issue (Balci, 1990). Therefore, computer simulation has several steps

which should be followed to perform a successful simulation study. These steps are presented in a comprehensive life cycle of simulation in Figure 13.

The first step in simulation involves identification of main goals and formulation of a problem. During problem definition, a communicated problem is rewritten as a well-defined formulated problem in mathematical terms and with logic structure. Then, the formulated problem undergoes verification and feasibility assessment of simulation is carried out. After assessment of simulation technique, a model is transferred into the simulation software. Subsequently, objectives of the model and system are defined. When the model is created at the first point, then it is verified. Verification is based on control of input data derived from experiments or real operations and output data which is given by the model. If model is investigated and behaves properly, then validation of a model is required. In validation step, it is necessary to analyze and check if conceptual model represents the real system. After model validation, design of different experiments of model may be performed. Experimentation involves various setups of simulation time, simulation runs and modifications of scenarios. Subsequently, the results of different experiments are analyzed to evaluate the model outcomes. In the last step of simulation, simulation results are interpreted and presented (Balci, 1990).

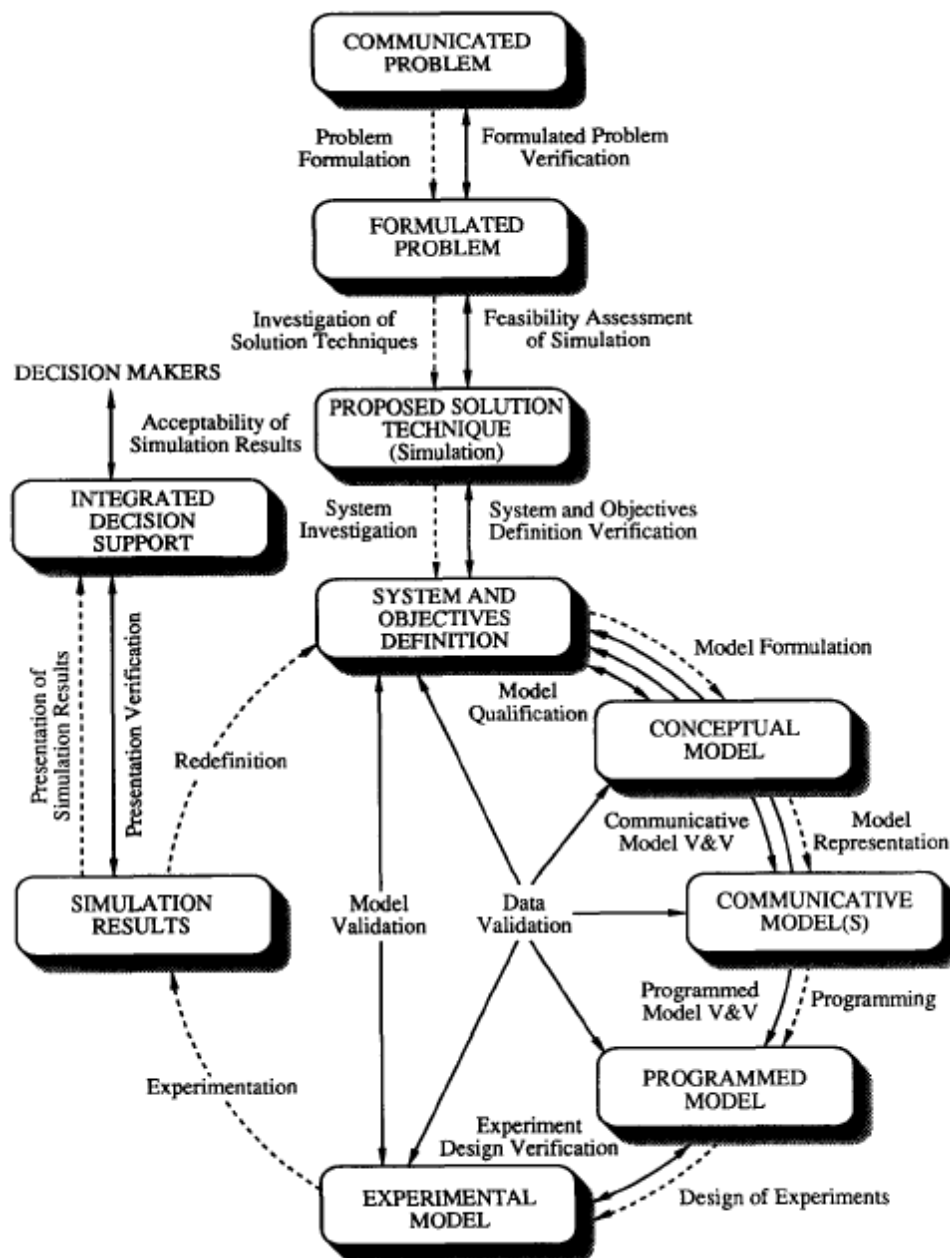


Figure 13 Life cycle of simulation study (Balci, 1990)

4 Simulation model development

Boliden started building a CAD-based model of a Kristineberg mine in 2012 to obtain complete mine layout, that will facilitate execution of different tests regarding fleet, autonomous machines, and work distribution. Since the scope of this thesis is to analyze operations for the whole 2016 year, a model was updated prior to the very first version of the mine layout.

4.1 SimMine software

SimMine is a simulation software which is based on discrete event simulation approach. This software is intended to simulate and evaluate every process of ongoing operations as well as upcoming projects. SimMine is dedicated for mining operations with focus on planning and optimization of production as well as profit maximization. In order to test different aspects of operations and their modifications, SimMine uses a statistical distribution functions to analyze processes behavior. This software has a simulation language environment with in-built modelling elements. SimMine requires no coding and the interface is fully graphical. It has an animation viewer which allows to track development procedures where machines' allocation and their behavior are emphasized. Furthermore, SimMine incorporates features like working shift set-up, selection of machinery and resources, advanced machinery and resources management settings, wide range of fleet parameters and their availability, settings for operations planning and scheduling, design of work rules and cycle characteristics, design of material and working costs, and tools to re-design or update CAD layouts. Statistical as well as de-bugging tools assist the process of model's behavior check-up. Furthermore, SimMine allows the user to set processes in consistent and logical sequence.

For the purpose of this thesis a development package of SimMine simulation software was used to conduct simulations over the analyzed period of 12 months and test different scenarios that might have a considerable potential for improvements regarding identified bottleneck and blast cycle operations. Development package enabled to design and schedule operations with reference to Kristineberg short-term plan, machines in service, working pattern, and blasting sequence. The mine layout together with SimMine features are depicted in Figure 14.

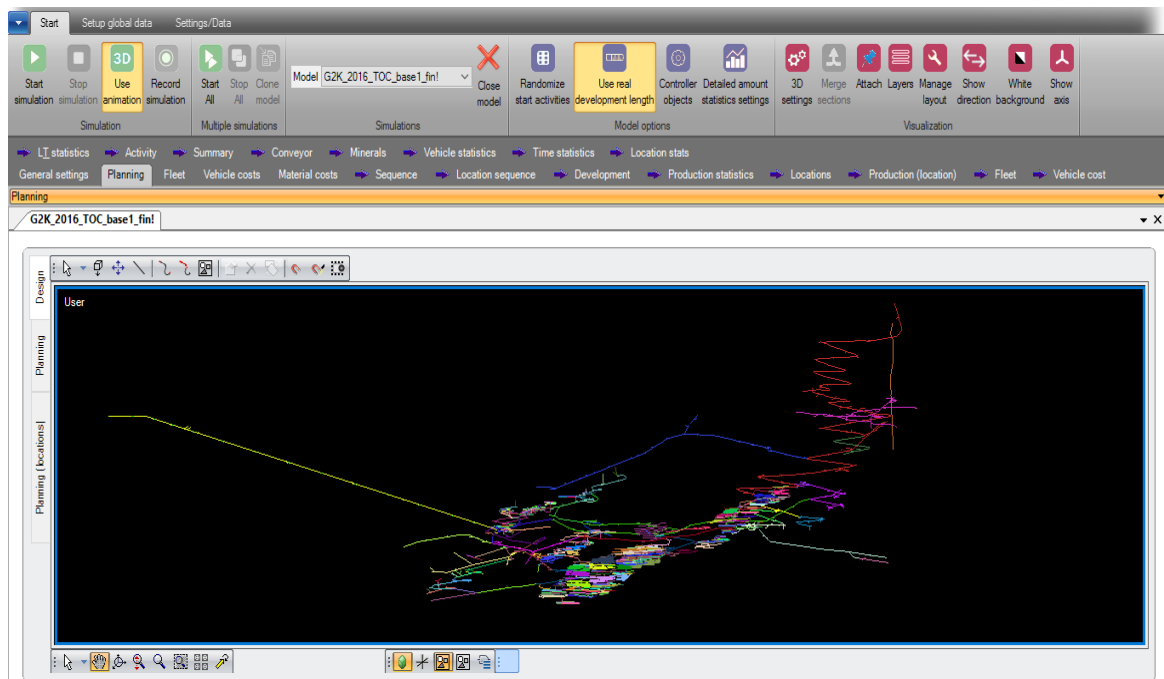


Figure 14 Kristineberg mine layout and SimMine modelling elements

4.2 Model construction

Construction of a simulation model which would reflect and imitate the nature as well as the performance of resources, was based on up-to date CAD mine layout. The model was completed with information and parameters regarding:

- Development plan including headings and sections
- Blasting plan
- Blasting cycle sequence
- Machines
- Working plan
- Working shifts

The data which was used for model building and model update was derived from:

- Production data for 2016
- Development budget plan for 2016
- Manufacturer's specifications
- Machines' utilization reports

- Machines' maintenance and availability reports
- Gantt Scheduler activities reports
- Gantt Scheduler efficiency reports
- Gantt Scheduler delay reports
- Boliden database and internal reports

Majority of reports and data regarding activities, efficiency, shift occurrences, and real-time operations were Excel-based. The main source of data with valuable information was Gantt Scheduler. This software is used by Mine-Operation-Center (MOC), where every aspect of operation within blasting cycle is planned, controlled, and recorded after its realization. Subsequently, the data from the Gantt Scheduler is verified and filtered to contain only transparent and accurate values.

To construct the model that mimics the operations performed in the mine, a budget plan and production data for 2016 year was used. This allowed to model a certain number of headings and sections to be operated and simultaneously be coherent with the short-term development and production plan. This part of modelling involved consistent set-up of dependencies between sections and modification of parameters regarding type of work location (e.g. drift, access drift, back-slash, stope). In total, 215 headings were modelled to being operated.

After selection of work locations, a work schedule and blasting plan was checked and updated. Only working shifts for Boliden employees were considered since some work performed by contractors during night shift is not included in the blast cycle. Weekly shift work plan is presented in the Appendix I in Table 7. There are two shifts (1st from 5:30 to 15:15, 2nd from 15:15 to 00:30). Furthermore, there are three blasting times (10:15, 19:15, and extra blast at 00:15). All operations were modelled to begin on 04.01.2016 and end on 01.01.2017. Vacation break was scheduled from 12.07.2016 until 08.08.2016, during which no blasting was performed. In total, 48 working weeks with blasting was modelled.

Data collected from the Gantt Scheduler was used to analyze work cycle times of respective machines, machines' efficiency, work locations, sequence of operations, and duration of development rounds. The mine layout already had some machines with their nominal specifications and cycle times, but it was updated prior to 2016. Gantt Scheduler data

enabled to update the model with values regarding fleet like preparation times and minimum and maximum cycle times of round completion. From Gantt Scheduler and Boliden Internal reports, availability and maintenance specifications were derived and used for every machine. This included Preventive Maintenance (PM), Mean-Time-Between-Failure (MTBF), Mean-Time-To-Repair (MTTR), micro faults, and major breakdowns. Data used for fleet specification set-up, facilitated input of accurate information. Altogether, 34 machines were used for development and production.

Additional source of information regarding machines' work characteristics including cycle times was Atlas Copco Certiq (ACC). However, ACC is a newly implemented measurement system in Kristineberg mine, and not every machine is connected to its network. There are only 4 bolters that are equipped with ACC technology. Therefore, only for 4 bolters the data from ACC was used as a comparison to data derived from the Gantt Scheduler.

Then, the sequence of blast cycle was checked and several working places were completed with processes including ventilation time and concrete curing time to truly imitate the reality. Every work location was analyzed and updated to keep the logic of operations in the cycle and be in accordance with Gantt Scheduler data.

Finally, the last source of information that was used in model preparation were observations conducted at the mine site. Mine observations were based on following shift's foremen, mining engineers, and machines' operators. During in-situ study a utilization of shift available work time was investigated, that it could be analyzed and compared to yearly average start and finish times of respective processes. Also, some obstacles and constraints were observed. Since observations were performed for a short time period, they were considered as a minor reference during model preparation, however, some constraints and limitations which had been noticed were used for further analysis of potential improvements.

During model building, data and parameters regarding some time characteristics like activity switch time, maintenance, maneuvering, machines' passing, actual shift start and shift end, and approximate times of activities' stops due to lunch break were based on average time measurements derived from Gantt Scheduler.

4.3 Model verification and validation

Verification process guarantees that construction of a conceptual model is translated in a right way into a computer model. Validation process guarantees that the model behaves accurately and is sufficient for further usage. Model verification and validation are essential and guarantee correct representation of the real system. Model which is accurately verified and validated can generate results which are approximate to those in reality (Salama, 2014).

In verification process, the constructed model was tested and assessed whether it performed properly and the representation of machines' activities was correct. Functioning and proper performance of simulation software was checked. Verification process was based on animations check since SimMine provides animation player and has a 3D environment. Additionally, the model was run under different conditions including changes in simulation time.

During verification process, it was very important to assess if the results given by the program were reasonable, the logic behind activities was preserved, and no data inconsistencies were found. Activity log files with list of all operations for respective machines were analyzed, and eventually the simulation model was verified.

Validation of the model was based on comparison between model's output data including blasting results and performance measurement, and outcome of the real system. Validation process was performed in accordance with the study period of 48 working weeks in 2016. The model's output was compared to production data for respective period.

The output of simulation model was 1806 blasts and 50657 operating hours, whereas in real system a total of 1804 blasts and 49984 operating hours were obtained. Furthermore, blasts obtained per one working week were checked. The model output stayed between 30 and 48 blasts per week, with average value of 37,63 blasts/week. In real operations, the minimum number of completed blasting rounds was 28 and maximum was 50 blasts per week, and the average value was 37,58 blasts/week. Since decimal number of blasts cannot be obtained, only integer number of 37 might be considered. This little difference between the results might have been caused by some randomness within the model. Nevertheless, results generated by simulation model were very close to those obtained in the real

operations. Therefore, model was validated and considered as accurate representation of the real system.

4.4 Simulation approach

The method for conducted simulations to define the baseline and analyze further scenarios for improvements was based on changes of parameters within the model and study one operation at the time. Changes and different scenarios (see Chapter 5) were implemented, differences were analyzed and compared to the baseline, what is depicted in respective graphs and charts. Every simulation was run at least 12 times. Each time different random seeds were generated. This process was performed to make sure that data is statistically correct. In simulations, a triangular distribution was chosen as distribution of work time. This affects how activity times are entered to a simulation model. Additionally, the highest priority was set for vehicles working mode. This affects how machines select their working location. Location with higher priority is operated first.

Comparison of multiple results within SimMine software was very limited. Therefore, simulations' results were exported to Microsoft Excel to facilitate comparison and representation of more than two simulations at one time.

To compare results of different scenarios to the baseline and indicate significant changes concerning operating efficiency as well as technical aspects, some key performance and result indicators were used. Chapter 4.5 contains description of implemented indicators.

4.5 Key performance and result indicators

It is essential to include right result indicators that will present differences between performed work under various conditions. According to Sjödin (2015), analysis of indicators should provide decision makers with some criteria when looking for improvements, and determine favorable and unfavorable points. Additionally, it is in demand to have universal set of measures, that could give sufficient overview of operations. Kaplan and Norton (1996), claim that indicators aside from actual assessment of the system should also provide measures of the future performance. Furthermore, to assess company operations and their profitability, some financial indicators would be critical to compare, however, financial issues including expenditures on improvements were outside of thesis scope.

4.5.1 Number of completed blasts

Number of completed blasts is simple, but very good measurement, which is used by mining engineers in production department. This indicator helps to measure mine production and analyze it according to short-term plan. Number of completed blasts is sometimes expressed in number of rounds. This indicator facilitates control of development and production progress. Number of completed blasts was chosen because of its reliability and unambiguity.

4.5.2 Number of sections

Number of sections indicates how many sections were operated by machines and how many of them were completed. Sections are included in headings, but one heading may comprise of several sections (e.g. one 60-meter heading comprises of four 15-meter sections). Number of sections reflects the advance of operations.

4.5.3 Face utilization

Face utilization indicates how much time machines needed to complete working face/heading/opening in relation to the total time of face/heading/opening being opened. This indicator may be used to decide how many faces/headings are necessary to be opened at the same time, to provide the fleet with work. Production engineers want to have as few working and active faces as possible, due to the costs of keeping the face opened. However, it is advisable to have more active faces to insure continuous production in case of face being inactive because of blocking by machine due to breakdown or any other random circumstances (e.g. rock burst).

4.5.4 Fleet utilization

Fleet utilization indicator is a good measurement of how machines are utilized over planned period of working time. This indicator is defined as the total worked hours by machines to total possible work time, where possible work time includes idle time, maintenance, and activity switch time. Moreover, this indicator may help to assess the utilization of available time, and be useful for investigating the idleness of machines.

4.5.5 Time utilization

Time utilization indicator is a measurement of effective work time compared to the total available shift work time. This indicator also includes working hours of machines. Time utilization may be used to assess the shift utilization for both short- and long-term time schedule.

Aforementioned KPIs are presented in Table 4, to give direct and clear overview of used measures.

Table 4 Key performance indicators

KPI	Figure	Unit ¹	Description
Number of completed blasts	Blasts	%	Total number of blasting rounds performed in the mine
Number of sections	Sections	%	Number of operated sections within headings
Face utilization	FaceU	%	Ratio of face total work time to face total opened time
Fleet utilization	FleetU	%	Ratio of machines work time to possible work time
Time utilization	TimeU	%	Ratio of effective work time to total available shift time

¹ Unit – to show the difference between different scenarios and baseline, unit was defined in percentage as distinguishable way of results comparison.

5 Simulation results and analysis

This chapter includes all results obtained during simulation studies, beginning with baseline and subsequently presenting specific scenarios. Cumulatively, 29 different scenarios were simulated. Tables and input data parameters regarding fleet and respective cases can be seen in Appendix I.

5.1 Baseline

Baseline is defined as a case which mimics very well operations performed in reality in the mine and is a credible representation of fleet behavior, what was confirmed by model verification and validation. Baseline will be used as a reference for further studies and comparison of results of various cases and their analysis.

Baseline shows the outcome of operations carried out within blasting cycle for the year 2016, including relevant production plan, shift work hours, adequate machines selection and their configuration. According to baseline, simulation results indicate that the total number of obtained blasts was 1806, what amounts to 7920 meters of development and production. This is the outcome of operations conducted on 252 sections of 215 different headings. There were around 19,5 operated faces per one working week. The average number of obtained blasts was approximately 37 blasts per week.

Utilization of fleet was 46,90% what is equivalent to 56,385 machines' hours, and utilization of time was 35,90% what corresponds to 50,657 effective work hours. The whole fleet was idle for approximately 52,170 hours, what is 43,38% of total available work time. Altogether, 34 machines covered 54,285 kilometers, what resulted in 7,584 hours spent on travelling.

Cycle time of one blasting round for production including all processes together with concrete curing time is approximately 26,92 hours. This indicates that operating time of machines is adequate and they are not performing too fast or too slow.

Additionally, bottleneck identification and partial bottleneck analysis will be based on results of a baseline case.

5.2 Bottleneck identification and analysis

Analysis of simulation results performed with the use of SimMine, allows to identify bottleneck. Identification of bottleneck with this simulation tool is similar to some of methods presented in Chapter 2.2. Fleet performance and duration of respective processes may help to localize the problem and assist to identify its root cause.

Identification of a bottleneck was based on study of machines' utilization throughout the year. Figure 15 illustrates a fleet utilization by vehicle type, where idle time is underscored. A vehicle or vehicles which have the smallest percentage of total idle time are considered to be the bottleneck. The idle time is a percentage of vehicle's total planned work time when the vehicle is supposed to work, but cannot find any work location. This approach partially corresponds to methodology proposed by Law and Kelton (2005), where machine with the highest average workload is the system's bottleneck.

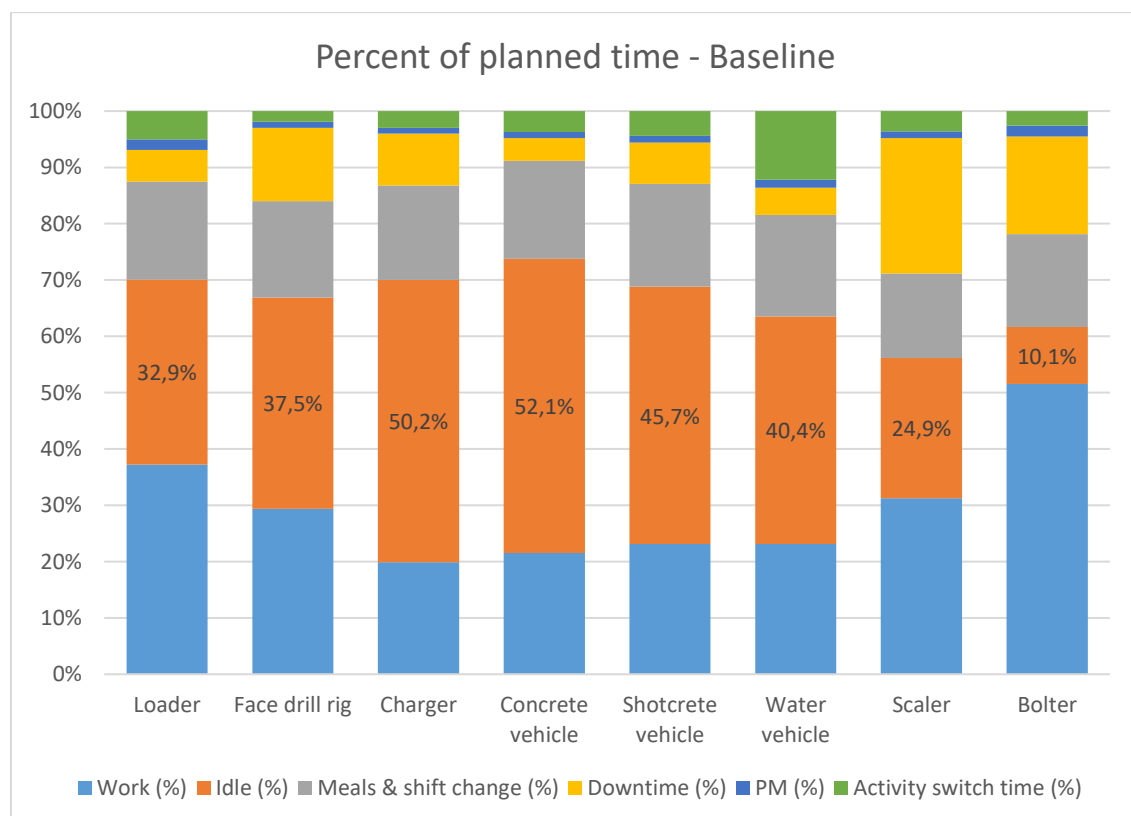


Figure 15 Fleet utilization data by vehicle type

As shown in Figure 15, bolters have the smallest amount of idle time and the highest utilization among other machines. Their idle and work time is 10,10% and 51,50% of planned time respectively.

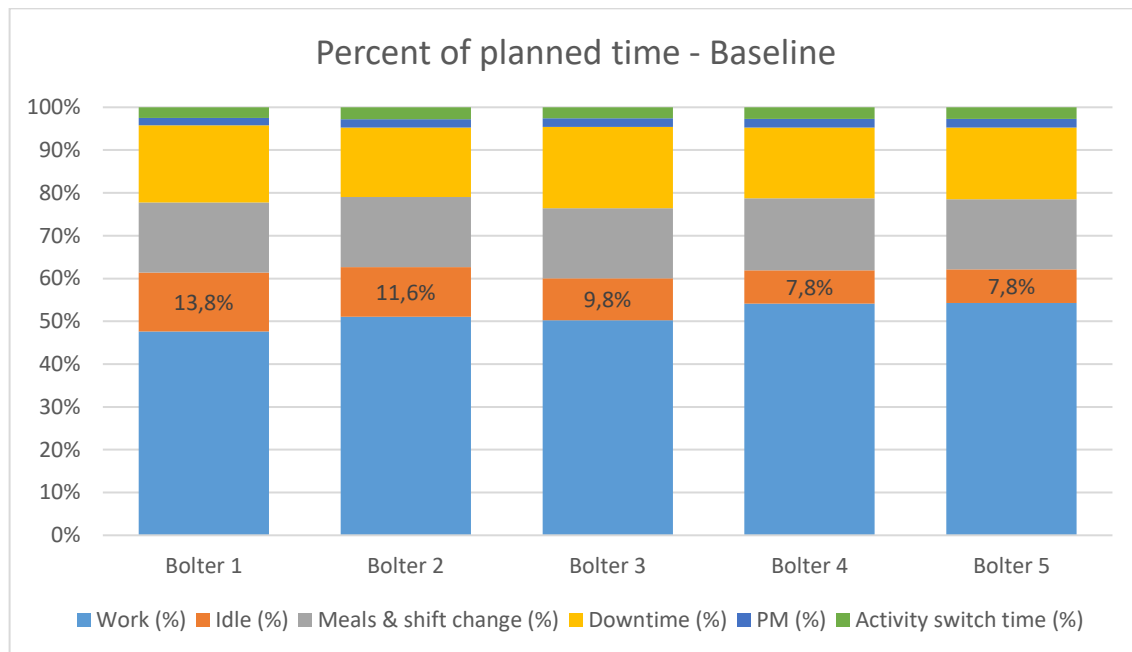


Figure 16 Utilization of bolters

In Figure 16 can be seen a detailed utilization of respective bolting machines. Idle time of bolters ranges from 7,80% to 13,80% of total planned time. This data confirms that bolters are highly utilized, but they still have some idle time which might have been spent on work.

A second measure derived from simulation results to study processes was activity wait time. The activity wait time is the amount of total time that the process had to wait until it commenced or worked with case. Figure 17 presents the total time that activities had to wait to get started or worked with. According to this measure, the activity which has the longest wait time is considered to be the bottleneck. This might also indicate that machines responsible for particular activity have too little capacity and might impede other machines in the cycle. This approach corresponds to some extent to methodology proposed by Law and Kelton (2005), where machine with the longest wait time is the system's bottleneck. Here is a group of machines responsible for specific activity.

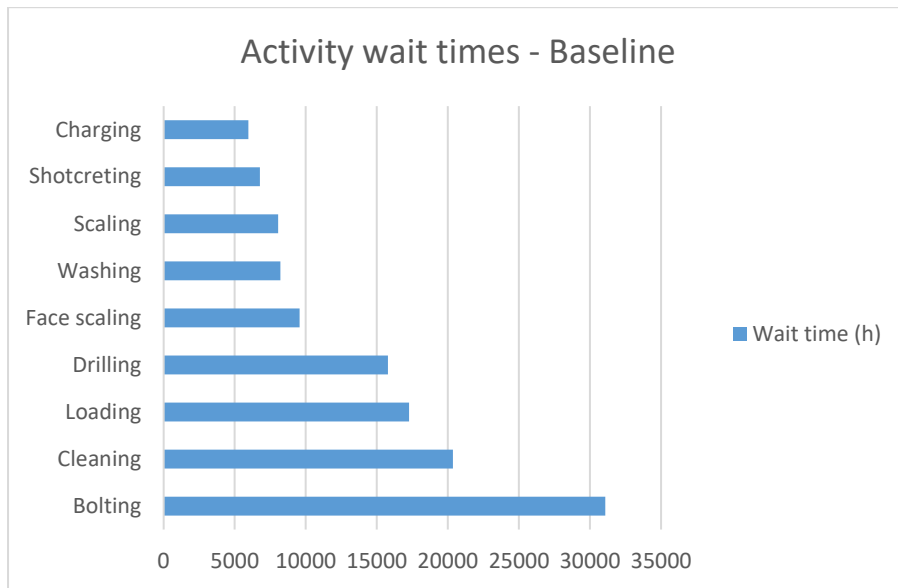


Figure 17 Wait times data for grouped activities

As can be seen in Figure 17, bolting activity is the one where wait time for this process to commence or work with is clearly the longest. Overall, it took 31,072 hours of waiting time for the whole group of bolters. This indicates that among other processes, bolting activity had to wait the longest amount of time for bolting rigs to start performing and completing their work. Activity wait time might demonstrate that bolting is a potential bottleneck.

Results derived from simulations including fleet utilization data of respective machines (see Figure 15 and Figure 16) and activity wait times of particular processes (see Figure 17) indicate that bolting activity is the bottleneck and bolting rigs are the most constrained resources among other machines. However, as it is for bolters' utilization, bolting rigs have around 10% of idle time, what might imply that their total planned work time is not fully utilized. Reason for that might lie in work shortages, finishing work too early, transportation obstacles, waiting for resources, operator travelling time or queuing time. These problems might find their reflection in waiting times of activities, where every work delay which is also due to meal breaks and shift change time is added to total wait time.

Utilization of bolters also indicates that considerable amount of total planned time, nearly 18% is downtime, which is due to minor and major breakdowns, and miscellaneous issues. This aspect influences operating availability of bolting rigs and contributes to increase of waiting time for the process to begin and end.

Reasons for bolting to be the bottleneck might be due to operating (operator skills, travelling), technical (capacity, performance) or organizational (planning, time utilization) issues.

5.3 Simulations for improvements

To analyze fleet utilization, performance, and operating capabilities of machines under various conditions, different scenarios were simulated. The main aim of these simulations is to study pre-defined bottleneck which is bolting activity performed by 5 bolting rigs. Additionally, this study is performed to present a potential for improvements regarding bottleneck exploitation and thereby increase in production. Possibilities of improvements are partially referring to assumptions derived from Theory of Constraints and its five focusing steps. For that reason, various changes indicate how bolting operation might be exploited to higher extent, how subordinate other resources, processes or aspects to bolting, and how to elevate bolting operation.

Simulation scenarios considered the following cases:

- Maintenance improvement – focus on preventive maintenance, mean time to repair, and mean time between failures of entire fleet and only on bottleneck vehicles
- Bolter efficiency improvement – focus on trimming of operation times of bolting rigs
- Changes within shift work time and blasting times – focus on extending available work time for machines and operating teams
- Additional operating places – focus on increasing number of working places (headings/faces) for machines
- Combination of cases – focus on maximization of production throughput by feasible and cumulative improvement

5.3.1 Fleet Maintenance

Maintenance consumes considerable amount of possible work time of machines. Reason for that is because of working environment and its rough conditions. Each machine from development and production fleet undergoes preventive maintenance once a week.

Though preventive maintenance might seem to be often, machines break down and meet some failures within hours of operations. Since maintenance contributes to machines availability, the aim of this approach is to analyze the increase of machines reliability by extending intervals between preventive maintenance (PM) and increase their uptime at work location.

Increase of intervals of PM means that machines are staying longer outside the workshop. Extended machines' uptime concerns increase of mean time between failures (MTBF) and shortening of mean time to repair (MTTR). For MTBF and MTTR micro faults were examined, since machines face more minor failures and disruptions at working face rather than major breakdowns. Minor faults are also easier to repair by mechanics or operators. Figure 18 shows results of conducted simulations with KPIs. Improvements (i.e. 5%, 10%, and 15%) mean that time between repairs is extended or time to repair is shortened. Input parameters are presented in Appendix I. Results of fleet utilization can be seen in Figure 31 and Figure 32 in Appendix II.

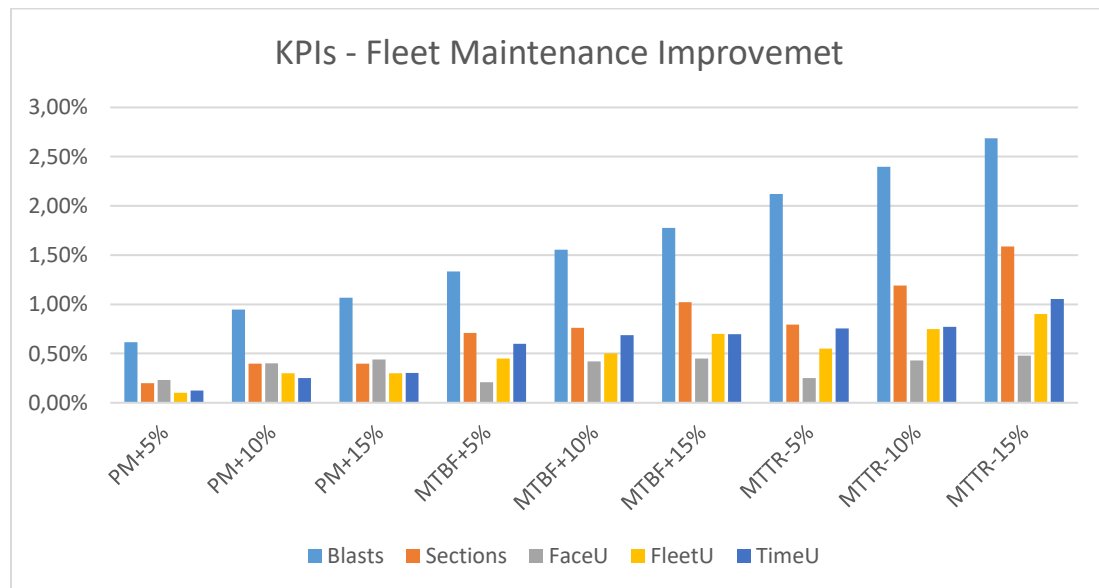


Figure 18 Simulation results for improved maintenance compared to baseline

As can be seen in Figure 18, in the first three scenarios for improved PM, machines are staying less time in workshop and can perform more work. Results show that production increased by slightly more than 1% for maximum case. However, when compared to

PM+10% case, the increment is not that significant as between first two cases. This may imply that machines despite longer intervals of PM face other breakdowns or loose their performance due to lower efficiency.

As the fleet of machines can spend more time on working the FleetU and TimeU are also higher. Higher FleetU and TimeU translates to faster face utilization and thereby there are more sections to be mined. This also causes that there are more blasts to achieve.

Results regarding fleet utilization (see Figure 31 in Appendix II) demonstrate that longer time intervals of PM increase uptime of some machines. Bolters are less idle and thereby can continue with their work, whereas drilling rigs or shotcrete machines are idler what could mean that they keep up with work plan or are given more extra work time.

Second scenario of improved maintenance concerns MTBF (see Figure 18). This improvement means that time between failures is longer and is also distributed over all machines as in the PM case. Simulation results show that in this case an increase in production is steeper than in previous situation. This is mainly due to bigger fleet utilization and time utilization, which for the MTBF+10% and MTBF+15% is almost doubled than for PM+15%. This is justified, because improved MTBF during scheduled work time has bigger impact than extension of PM intervals. Increase of MTBF by 15% results in 1,79% higher production. This is the result of better FleetU and TimeU, where also number of mined sections is considerably higher. In maximum scenario for MTBF there is 1% increment of sections. Increase in number of mined sections affects the tempo of face advance. FaceU increases, but there is slight difference between MTBF+10% and MTBF+15%, what might imply that machines work at steady rate but face less problems at working face.

Fleet utilization results (see Figure 32 in Appendix II) demonstrate that longer time between failures increase utilization of bolting rigs. Their idle time is smaller by 0,5% whereas for most of machines idle time is bigger. Bigger idle time of other machines might be caused by bolting rigs, which are given more time to complete their work, but at the same time keep other machines waiting at the face.

The last scenario of improved maintenance concerns MTTR which is also presented in Figure 18. In this scenario assumptions regarding faster repairs of failures by mechanics

crew or operators were considered. Reason for that is many minor faults that machines face during their work.

Simulation results indicate that shorter repair times have the most significant influence on production in that case. Production increase ranges from 2,12% to 2,69% for respective improvements. For MTTR-15% increase is the highest, a reason for that is because of higher TimeU and FleetU and thereby also number of mined sections is considerably higher. Similarly like in MTBF case, difference between MTTR-10% and MTTR-15% for FaceU is slight. However, this implies that machines stay longer in working mode and less time at standstill while waiting for repair.

Steeper increase in production for MTTR case, when compared to PM and MTBF scenarios might be due to fact that machines face numerous minor faults during their work time which significantly affect their efficiency and hinder performance. Therefore, improved MTTR translates to quicker coping with miscellaneous impediments. This is justified by increased fleet utilization (see Figure 19) and time utilization.

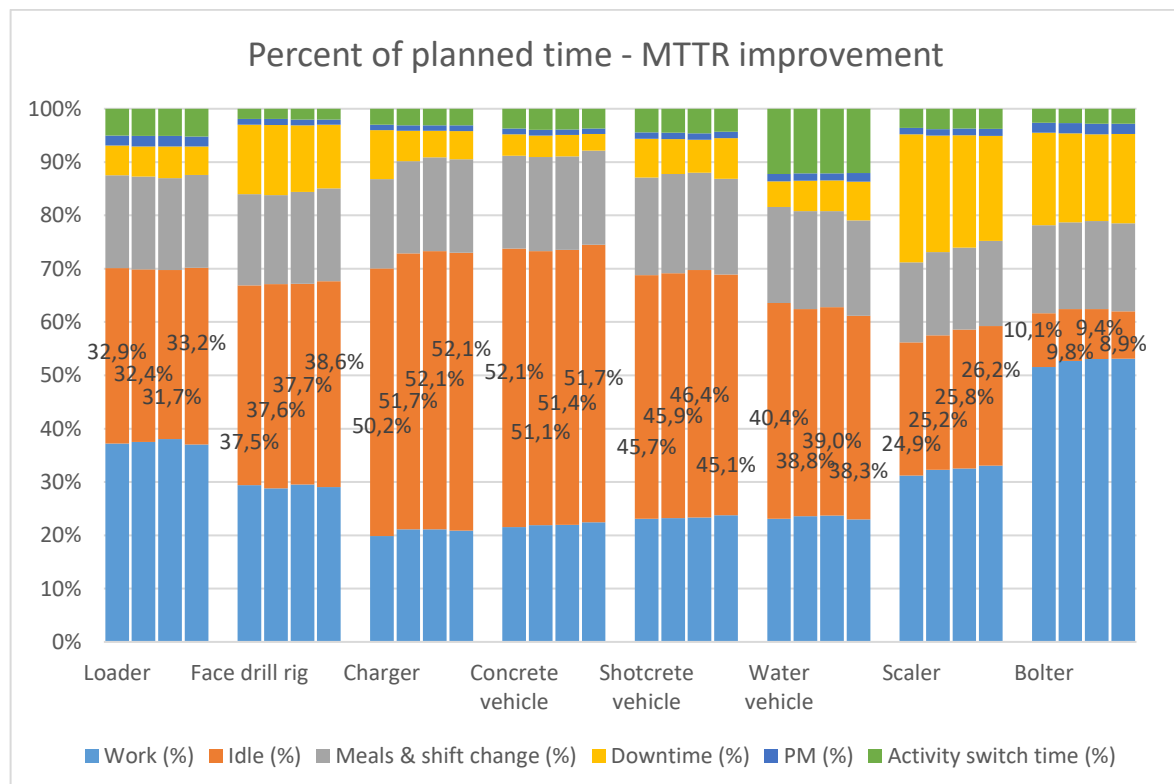


Figure 19 Fleet utilization data for improved MTTR compared to baseline

As can be seen in Figure 19 (first bars of respective machines illustrate baseline and next bars are 5%, 10%, and 15% cases), work percentage of machines is slightly higher when compared to baseline. Interesting fact is that bolter which is the most constrained resource among the whole fleet can operate to higher extent and thereby its idle time is lower – 8.90% for MTTR-15%. This means that with improved MTTR the bottleneck is busier what acts toward production increase. However, some machines are idler despite decrease of their downtime and increase of work percentage. This means that these vehicles sometimes must wait for bolting rigs to finish their activity.

5.3.2 Bolting rigs maintenance

This simulation scenario is similar to previous approach, however, in this case only bolting rigs are considered to be the only group of machines which are involved in integrated maintenance plan. Integrated maintenance plan assumes that improvements of PM, MTBF, and MTTR are combined and implemented simultaneously. Furthermore, assumptions remain the same, where time between scheduled maintenance is extended, mean time between failures is longer, and mean time to repair is shorter. Improvements of 5%, 10%, and 15% are distributed equally over maintenance of bolting rigs, this means that for BRM+5% (see Figure 20), PM interval and MTBF is 5% longer, and MTTR is 5% shorter.

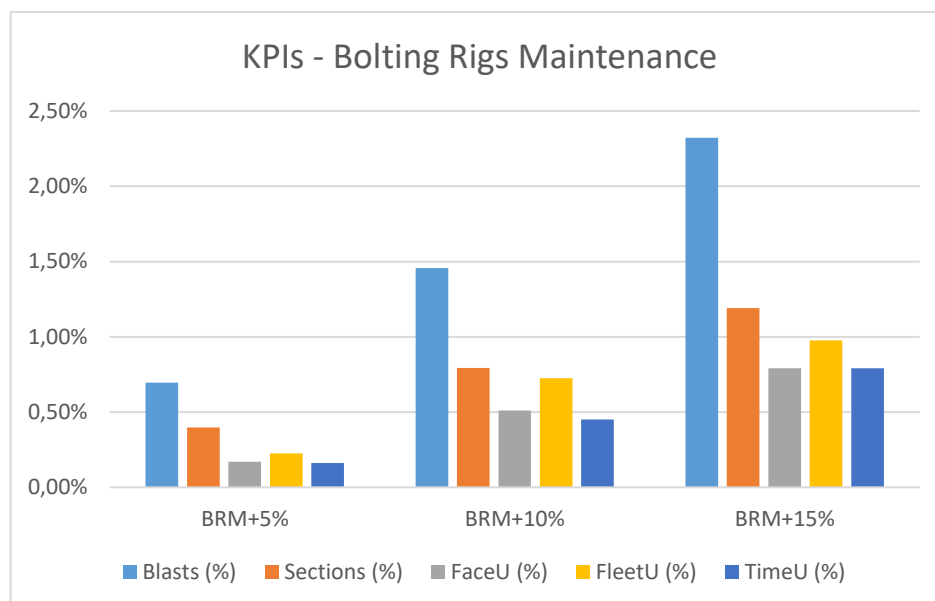


Figure 20 Simulation results for combined maintenance of bolting rigs compared to baseline

As depicted in Figure 20, simulation results show significant difference in operating efficiency and thereby production results are obviously higher when compared to baseline. Production increase ranges from 0,7% up to 2,32%. This improvement of production finds its justification in consistent increase of other parameters, especially in fleet utilization (0,22% up to 0,97%) and by that bigger number of mined sections (0,4% up to 1,19%) and higher advance of working at the face (0,17% up to 0,79%). This uptrend is visible and clear. For maximum scenario of bolting rigs maintenance improvement (BRM+15%) fleet utilization is higher by nearly 1% and therefore time utilization is also higher by 0,79%; FaceU is higher by the same percentage; production increase equals 2,32% more than baseline.

Maximum case (BRM+15%) could be compared to holistic feet improvement for MTTR-10% where production rose by 2,4%, and time utilization was 0,77% higher. However, when compared to MTTR-10%, all the vehicles were involved in the change of one parameter. In BRM+15% only 5 bolting machines were involved.

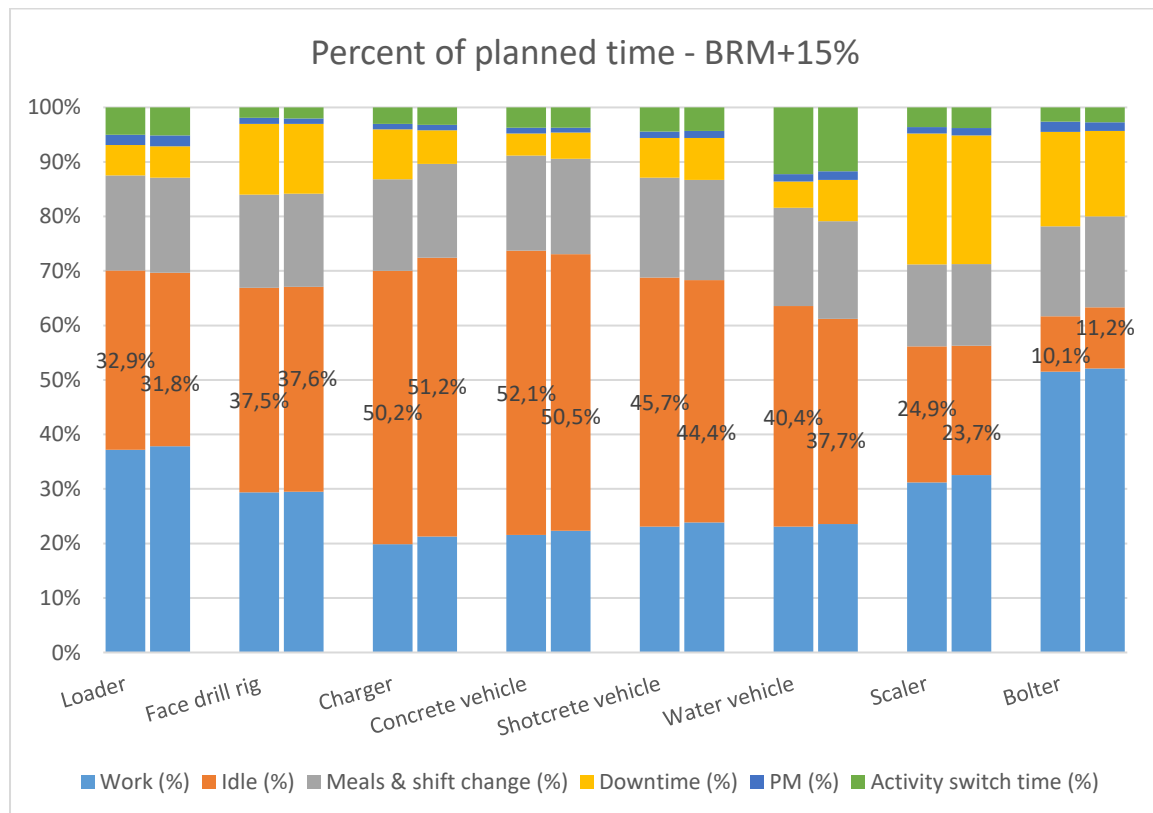


Figure 21 Fleet utilization data for combined maintenance (+15%) of bolting rigs compared to baseline

Fleet utilization results (see Figure 33 and Figure 34 in Appendix II) show gradual increase of idleness of bolting rigs. Idle time ranges from 10,80% up to 11,20% what corresponds to 0,7% and 1,1% higher result than for the baseline. Behavior of rest of the vehicles changes for respective improvements. Machines like face drill rigs and chargers are idler when compared to baseline. This situation might be caused by bolters which have more time to operate, they face less impediments and thereby can complete their activities faster. Therefore, drilling rigs and chargers which are next in the cycle do not have to wait for bolters at the face.

As can be seen in Figure 21, integrated maintenance of bolting rigs influences not only bolters' efficiency, but also other vehicles are operating to slightly higher extent. Some machines like loader (1,1% difference), shotcrete vehicles (1,3% difference) or scalers (1,2% difference) are less idle. This implies that they are not impeded by bolters, and can operate more effectively.

Simulation results for improved and combined maintenance of bolting rigs indicate that for scenarios like BRM+10% and BRM+15% might obtain similar results as for those conducted for the whole fleet maintenance, MTBF+10% and MTTR-10% respectively. Therefore, integrated maintenance of bolters presents interesting potential for improvements if further decisions are to be made. This scenario shows gradual increase in production as well as slight debottleneck of bolting rigs.

5.3.3 Bolting rigs performance

The approach of this simulation scenario is to analyze fleet performance and production results with shorter operating times of bolting rigs. This study involves 5 different setups of bolting machines. Only 5 bolters are considered as it is the number of machines that are currently in Kristineberg mine for production and development, therefore no additional bolting vehicle was added during simulation.

Since bolting rigs are considered to be the bottleneck, shortening of operating times assumes faster completion of rounds and thereby increase of bolting efficiency. In reality, this might be obtained by development of operator's skills to handle machine appropriately and perform work with precision while omitting unnecessary maneuvers. Table 15 in Appendix I presents input parameters of bolting operating times.

To complete one development round which is around 4,5 meters long, bolting rig has to perform a set-up of approximately 45 rock bolts. The estimated time of completion of this activity is 5,6 hours, what includes both drilling and bolting. On average 8 bolts per hour are applied. Since bolting is a complex operation and needs continuous manual maneuvering, an operating time is a substantial factor influencing its efficiency. Shortening of operating time was to analyze under which conditions bolters could not be considered as bottleneck.

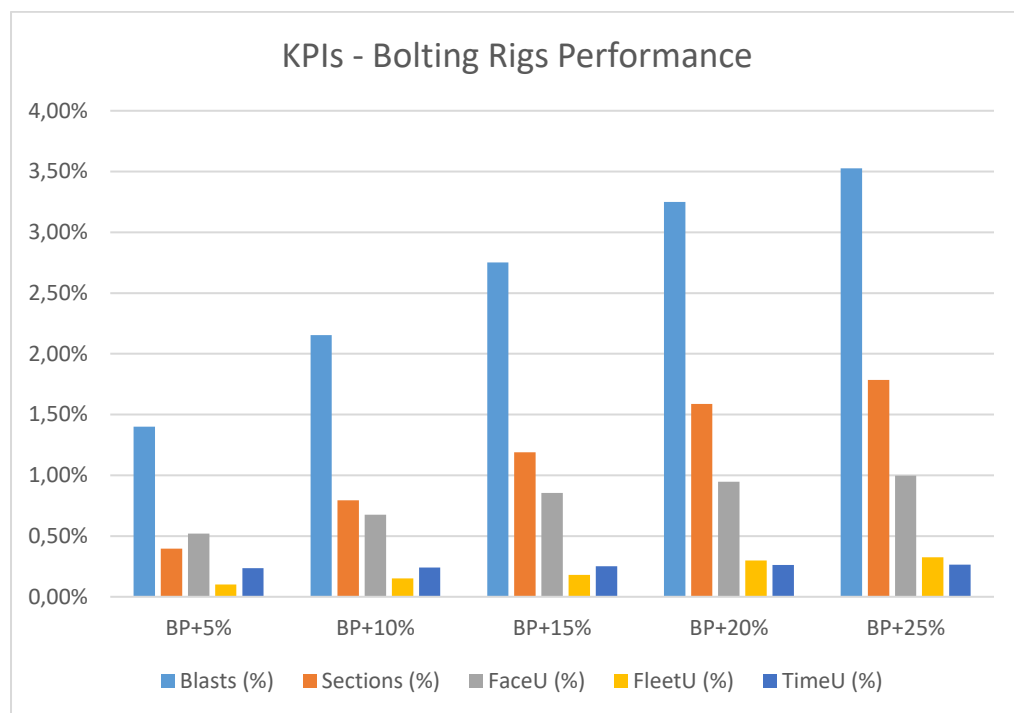


Figure 22 Simulation results for bolting rigs performance compared to baseline

Figure 22 depicts simulation results with improved performance of bolting rigs. BP+5% denotes 5% higher performance of bolting vehicles. It means that operating time is 5% shorter what is equivalent of approximately 18 minutes faster development round for one bolter. As can be seen in Figure 22, a distinct trend of production and performance indicators developed. Production increase ranges from 1,40% up to 3,53%. Increase of production is due to faster operating times of bolting rigs. Thereupon less time is needed for round completion, what translates to higher face utilization and thereby more sections can be operated. Time utilization stays nearly the same for all scenarios and its between

0,23% and 0,26%. Higher time utilization is result of more effective work but its increase is not that substantial as for previous scenarios. Fleet utilization is also higher and ranges from 0,1% up to 0,32%. This slight increase is due to the fact that machines are not that often at standstill, and can earlier perform their activities. However, slight increase indicates that machines might face maintenance problems or impediments at work face. For scenarios BP+5% - BP+20%, the increase in production is sharper than for the last case (BP+25%). Difference for BP+25% equals 0,28%, where for other cases its between 0,5% and 0,75%. This might imply that bolters are no longer the bottleneck. Also, face utilization is almost at the same level, though bolters are operating faster. This situation might be due to a new opening and therefore number of sections increased.

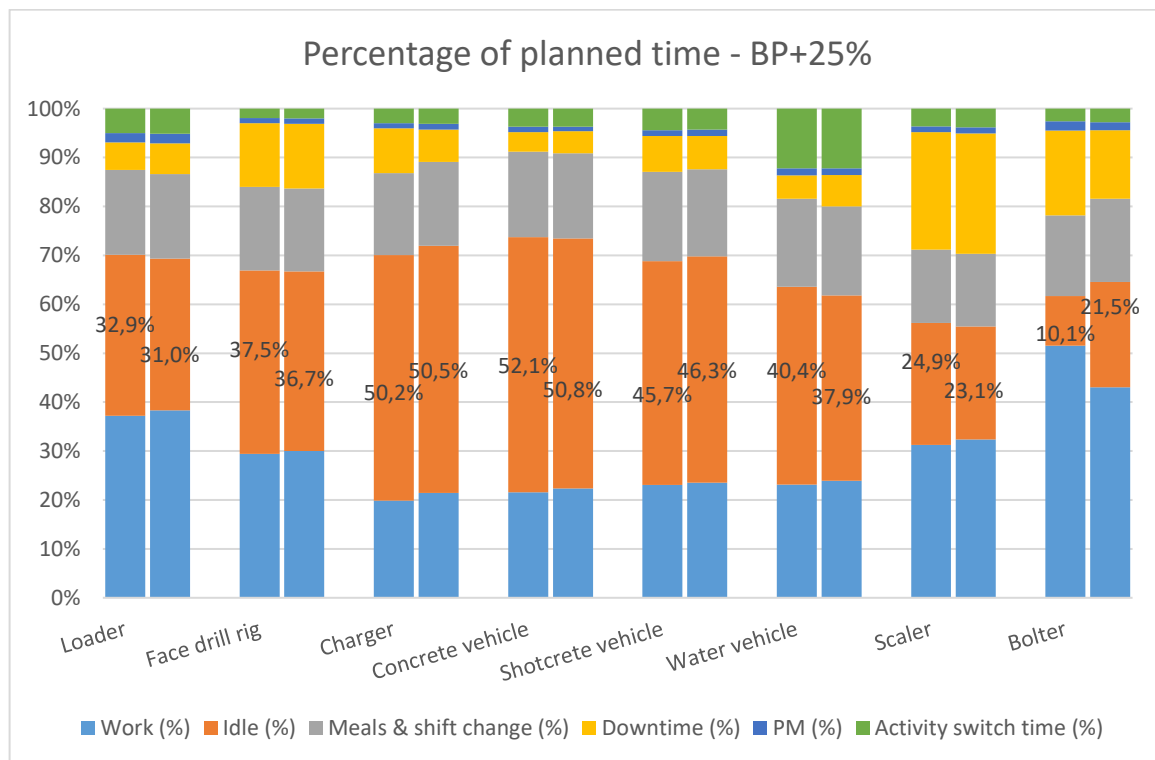


Figure 23 Fleet utilization data for improved performance (+25%) of bolting rigs compared to baseline

Fleet utilization results can be seen in Figure 35 - Figure 38 in Appendix II. Results indicate that idle state of bolting rigs is rising notably. This significant increase is because of faster realization of bolting activities due to higher efficiency and therefore bolter's work is more effective. Bolters' idle state ranges from 13,20% even up to 21,50%. Behavior of rest of

machines is also affected by bolter's shorter operating time. As bolters are operating faster other machines like loaders, concrete vehicles or scalers are less idle (scenarios BP+5% - BP+15%) and can perform more work with accordance to the plan. But for the same scenarios, machines like face drill rigs, chargers or shotcrete vehicles are idler, what might imply that their work potential is not fully utilized. However, this situation slightly changes for face drill rig and shotcrete machine in the last two scenarios.

As can be seen in Figure 23, for maximum improvement of bolting operating time, idle time for the bolters is more than doubled when compared to baseline. Higher efficiency of bolting rigs enables other machines to have more work. Simulation results demonstrate very interesting direction of fleet utilization. It is noticeable that while bolters' idle state increases, and its work state declines, the work percentage of all other machines raises. At the same time production results are higher. Similar trend is also for cases BP+10 – BP+20. This situation (cases BP+20, BP+25%) implies that bolters easily keep up with the rest of the fleet and additionally could be given more work to perform. Therefore, bolters are no longer considered as bottleneck. Constraints might be because of too low number of active faces/headings or planning limitations.

Simulation results for development of bolters performance show significant potential for production increase and might be of high importance in decision making process. However, maximum scenarios should be broader analyzed in terms of technological and technical capabilities.

5.3.4 Shift and blasting times

Utilization of available shift time is very important in terms of use of resources, distribution of workload, and dispatching of machines. Appropriate organization and time management may act toward increase of resources productivity, operating efficiency and thereby contribute to development of production throughput. Furthermore, proper time management and work schedule may improve exploitation of system's bottleneck.

This simulation scenario is about to analyze different work distribution over shift time and involves changes in start and stop times with emphasis on shift breaks. Additionally, changes in blasting times are included and analyzed. In simulation model, average start and stop times of actual work were implemented to reflect time utilization to the best degree.

For the baseline, blasting operations are conducted during lunch breaks (10:15 and 19:15) and additional blasting is performed at 00:15. Three out of four simulation scenarios (Shift I, Shift II, Shift III) include only two blasting times. This new blasting scheme assumes blasting in between shifts change at 15:00, and at the end of the second shift at 00:30. These three scenarios are about to analyze utilization of available time and exploitation of machines when shorter and more flexible lunch break is implemented, and there are longer periods between blasts, except for Shift I which assumes no lunch breaks. One simulation scenario (Shift IV) is similar to the baseline, where three blast times are preserved, but slightly longer work time is considered. Shift work times and blasting can be seen in Table 5. Input data regarding start and stop times of respective shifts is presented in Table 8 - Table 11 in Appendix I. This approach takes into consideration some organization and work policy changes to assist the progress of bottleneck exploitation and to subordinate working scheme to bottleneck working possibilities that it could be utilized more effectively.

Table 5 Shift times with blasting for simulation scenarios

	Blasts	Time	Start	Stop	Start	Stop	Start	Stop	Start	Stop	Hours/day	Hours/week
Base-line	3	Mon-Sun	6:15	9:30	11:00	14:35	16:00	18:45	20:00	23:30	13:05	91:35:00
Shift I	2	Mon-Sun	6:30	14:15	16:15	23:15					14:45	103:15:00
Shift II	2	Mon-Sun	6:15	10:00	11:00	14:30	16:00	18:45	20:00	23:45	13:45	96:15:00
Shift III	2	Mon-Sun	6:15	10:00	11:00	14:30	16:15	19:15	20:15	23:30	13:30	94:30:00
Shift IV	3	Mon-Sun	6:15	9:45	11:15	14:30	15:45	18:45	20:15	23:45	13:15	92:45:00

As can be seen in Table 5, working plan for Shift I assumes the most working hours per day and by that possible work time per week is the highest. It equals 103,25 hours, but it excludes lunch breaks. Shift I and Shift II assume more working hours than baseline and it is 96,25 and 94,5 hours respectively. The last shift with 3 blasts assumes only 1,16 hour more work time per week.

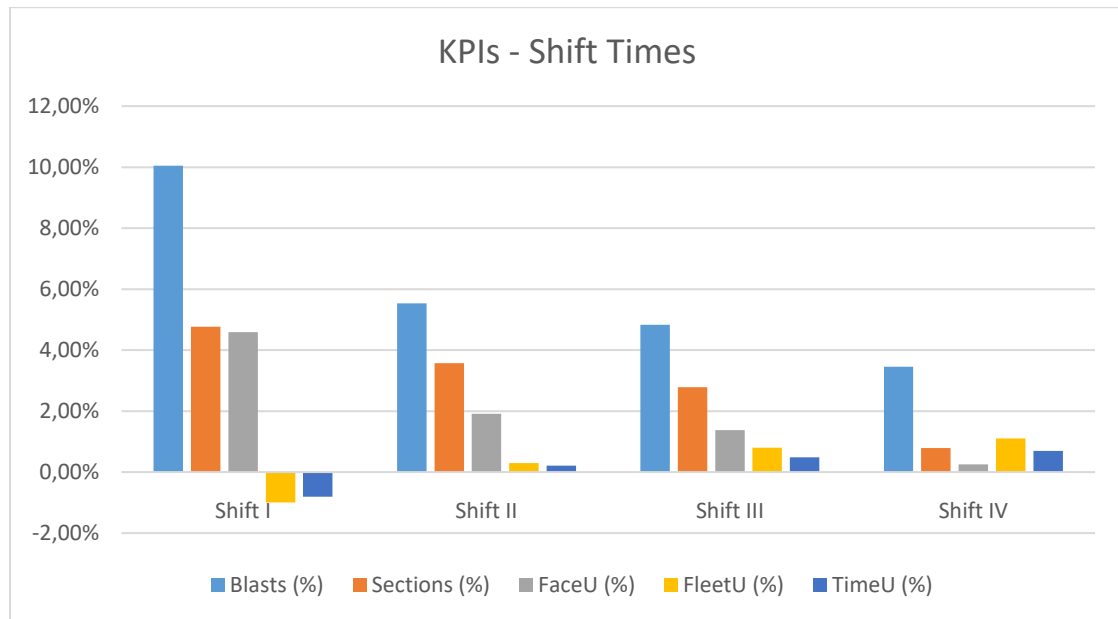


Figure 24 Simulation results for different shift and blasting times compared to baseline

Figure 24 depicts simulation results for different shift structure and blasting times. Production and performance indicators are well distinguishable. This difference is mainly due to changes in possible work time. Increase in production is sharp and it ranges from 3,45% up to 10,04% more than standard case. But this visible trend is sustained only for 3 parameters: Blasts, Sections, and FaceU. Reason for that might be because of not fully used available time potential. Increase in production is due to higher face utilization which is quite distinct for Shift I, Shift II, and Shift III. Higher face utilization transfers into more operated sections which ranges from 2,79% up to 4,76% more than baseline. Higher face utilization and more operated sections is a result of more possible work time. This implies that machines are given enough time to complete their activities and can smoothly keep up with the working plan. Results regarding Shift I, show the highest increase in production, that reaches 10%, number of operated sections and face utilization is nearly the same and is slightly above 4,5%. However, fleet utilization and time utilization are both lower by nearly 1% each. This decline indicates that total possible work time is not fully utilized, and thereby vehicles' utilization is lowered. This implies that there might be potential for higher utilization but more working places are needed, therefore, more headings/faces should be facilitated. But it is important to mention that in these scenario machines are working continuously during shift time and might face more breakdowns and failures what affects

time and vehicles utilization. When it comes to Shift II and Shift III, all performance indicators are higher than baseline, even though more work time is available. For Shift II, FleetU and TimeU is almost two times smaller than for Shift III, and equals 0,3% and 0,22% respectively. Despite there is more possible work time than in Shift III, this situation might be due to slightly too less working places and work potential is not utilized or machines are facing more maintenance problems. However, there is a significant increase in production for scenarios where only two blasting times are applied.

Interesting results can be seen for Shift IV. Production growth is 3,45% higher than for the baseline. Number of sections (0,79%) and face utilization (0,25%) are slightly higher. But fleet utilization (1,1%) and time utilization (0,69%) indicate better results than for the previous shifts. This implies that even with three blasting times per day, but with more than 1 hour of work per week, vehicles and time can be more effectively utilized in the whole year scale.

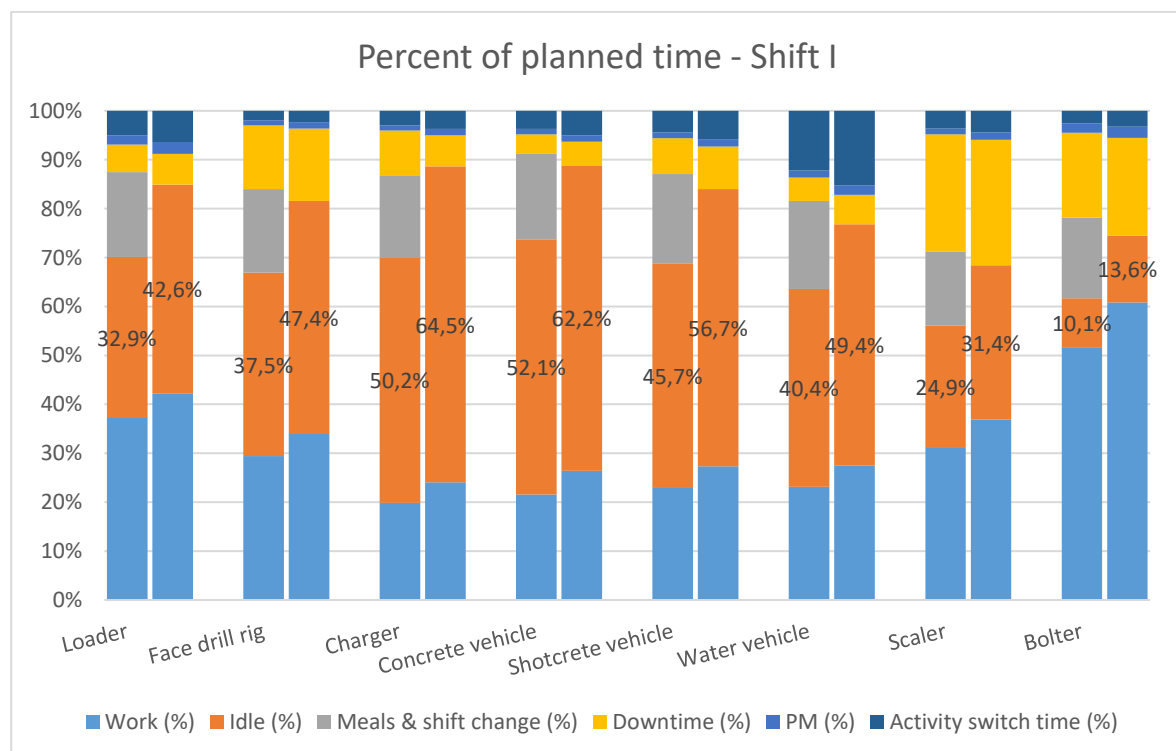


Figure 25 Fleet utilization data for Shift I compared to baseline

Fleet utilization results for respective shifts and blast scenarios can be seen in Figure 39 - Figure 41 in Appendix II. As can be seen for scenarios Shift I, Shift II, and Shift III a distinct trend of machines' behavior developed. For all machines except for bolter in Shift III scenario, idle states are higher and at the same time work percentage is increased. This indicates that fleet can operate to higher extent and more work can be performed, but on the other hand increased idle state suggests that some more working places are needed to make vehicles busier. In Shift II scenario bolting rigs which are considered to be the bottleneck have 0,4% higher idle state and 1,1% more work, therefore increase of possible work time acts toward bottleneck exploitation but idle state suggests that bolting rigs could be made busier. In Shift III scenario, where vehicles have less possible time for operations, bolting rigs are less idle by 0,4%, but their utilization is 3,7% higher. This might be because of keeping high operating rate while having less time than in Scenario II. Idleness might be also lowered by higher downtime increase of 1,1%. Shift IV scenario shows that all machines are less idle and bottleneck is slightly more exploited. Bolters are 0,2% less idle and can perform 0,4% more work. But Shift IV includes three blasting times, therefore shorter possible work time makes machines busier when compared to other shift scenarios.

As can be seen in Figure 25 vehicles have sharp increase in their work utilization which is on average 5% higher for majority of machines, but for bolter it is almost 10% higher. This increase is due to exclusion of lunch breaks, what results in more operating efficiency of vehicles. However more operating time finds its disadvantage in occurrence of more breakdowns; therefore, downtime of every machine is higher. Idle state of vehicles is much bigger when compared to baseline. Its difference ranges from 3,5% up to 14,30% for respective machines. This is because of too less active headings and is confirmed by lower overall time utilization in year scale.

Simulation results for shift and blast time changes show high potential for production improvement, where more work on bottleneck can be performed. However, managerial and working policy changes must be considered.

5.3.5 Additional working places

This scenario analyzes utilization of resources when more places are available for development and production. An approach of this simulation assumes additional headings which are included in yearly production plan. Extra headings were added to original plan for 2016.

The main assumption in form of additional headings in the work plan might contribute to better utilization of vehicles. An idea behind this scenario is to create a work buffer for machines that they could be dispatched to available work locations instead of being kept waiting and impeded from operating at the face. Moreover, this scenario assumes higher exploitation of bottleneck, presumably, to its utmost possibilities. This may have a positive impact on production throughput.

Original plan for year 2016 included 215 headings. During simulation studies 4, 6, and 11 more headings were added respectively. Operations were simulated for standard shift times with three blasts.

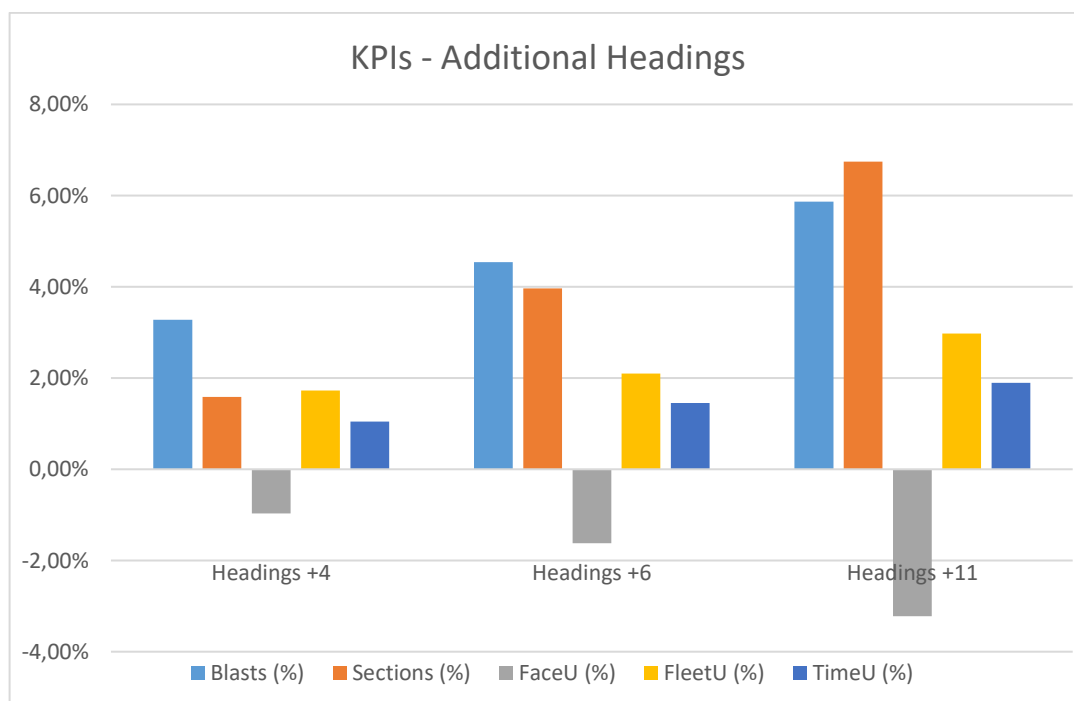


Figure 26 Simulation results for additional headings compared to baseline

Simulation results for additional number of headings depicted in Figure 26 show significant difference when compared to baseline. Substantial impact on production, vehicles and time utilization can be seen. A visible trend which indicates gradual growth of four parameters (Blasts, Sections, FleetU, TimeU) with simultaneous decline of FaceU is noticeable. This trend develops when more headings are made available. Production increase is quite sharp and ranges from 3,28% up to 5,87% more than baseline. Increase in production comes from higher number of operated sections. Growth in operated sections is 1,59%, 3,97%, and 6,75% for respective cases, at the same time face utilization is lowered by 0,97%, 1,62%, and 3,22% for corresponding cases. Therefore, increase in sections comes from additional headings. Even though face utilization has declined, and openings need more time to be fully completed, vehicles and time utilization is higher. For maximum case FleetU amounts to 2,98% and TimeU is 1,98% more than standard case. For other two cases, these indicators are also higher. This might indicate that machines are not performing faster, but instead of being kept waiting, can find more available work locations and be dispatched to other faces.

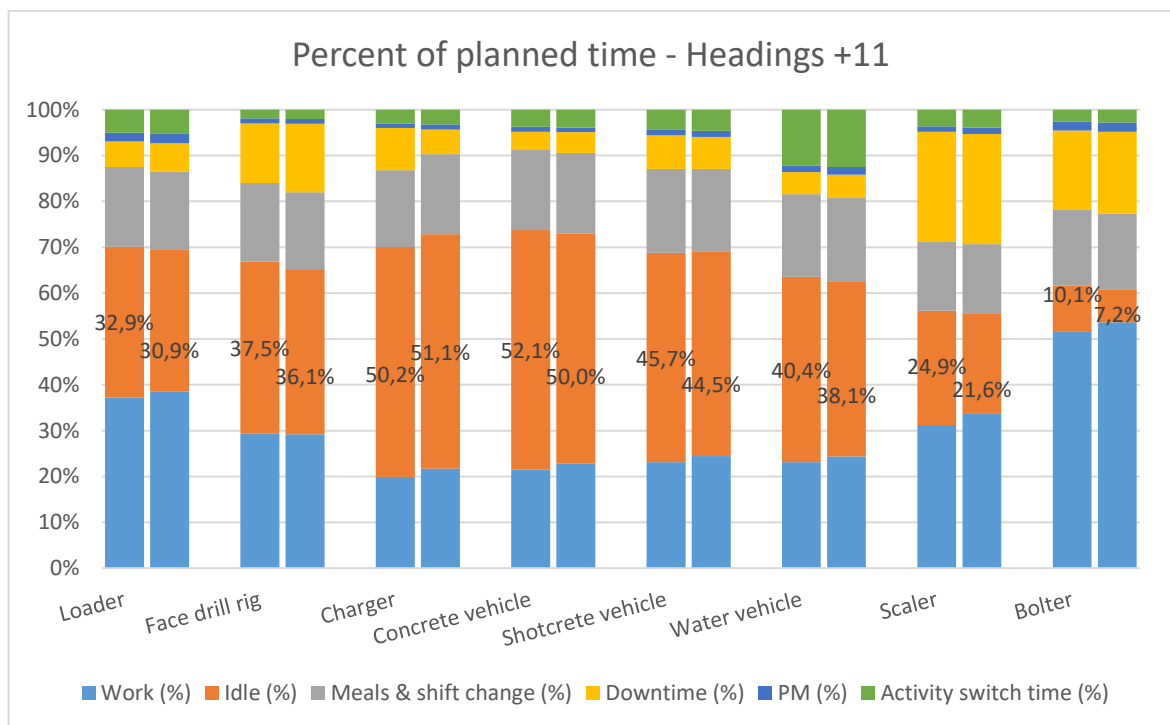


Figure 27 Fleet utilization data for 11 additional headings compared to baseline

Fleet utilization results for additional headings scenario can be seen in Figure 42 and Figure 43 in Appendix II. Results indicate that all machines tend to perform more activities, and thereby their work percentage is higher for every case. Higher utilization of machines is confirmed by lowered idle state. But some machines like chargers and shotcrete vehicles are slightly idler especially for Headings+4 scenario, whereas, for Headings+6 and Headings+11 (see Figure 27) scenarios only chargers remain idler. This might be because of overperformance of these machines during work. As can be seen for bolters, their utilization is gradually increasing over raising number of headings. Their idle state is decreased by 1,3%, 1,9%, and 2,9% for respective scenarios. This indicates that bottleneck might be exploited to higher extent, but its necessary to remember that with higher exploitation they might face more maintenance problems and disturbances during work. This is confirmed by growth in downtime of bolting rigs, which raises by 0,1%, 0,3%, and 0,6% respectively. Also, due to more work preventive maintenance raises slightly.

Figure 27 shows results for maximum headings added to original development and production plan. Utilization of bolting rigs is higher by 2,2% than for the baseline, at the same time their idle state is decreased and amounts to 7,2%. These results indicate that vehicles might be more exploited when additional working places are available, therefore, an assumption of work buffer may be positively considered.

Additional headings act toward production increase despite bolting rigs which need the most amount of time for round completion, and are the most constrained resource in the blast cycle. However, reduced rate of face advance might have an impact on costs, which may rise due to longer time of headings being opened. Simulation results show potential for development, but specific measures and plans like vehicles dispatching, and update of production plans should be investigated.

5.3.6 Combination of scenarios

The last simulation study involved combination of particular cases to see the maximum and also achievable result of integrated development. Combined scenarios of enhanced working procedures and operating aspects reflect the process of ongoing improvement (POOGI), which implementation might show the prospective potential for development of operations and production in Kristineberg mine.

Table 6 Simulation changes within combined scenarios

Combined 1	Combined 2	Combined 1B	Combined 2B
Normal Shift	Shift III	Normal Shift	Shift III
Fleet Maintenance +10%	Fleet Maintenance +10%	Bolters Maintenance +10%	Bolters Maintenance +10%
Bolters Performance +10%	Bolters Performance +10%	Bolters Performance +10%	Bolters Performance +10%
11 Extra Headings	11 Extra Headings	11 Extra Headings	11 Extra Headings

Combination of scenarios with different setup can be seen in Table 6. In configuration of fleet and bolters' improvements reasonable parameters were chosen, since improvement of 10% in maintenance and capacity might be faster to attain. For changes in management and organizational procedures Shift III with 2 blasts was chosen.

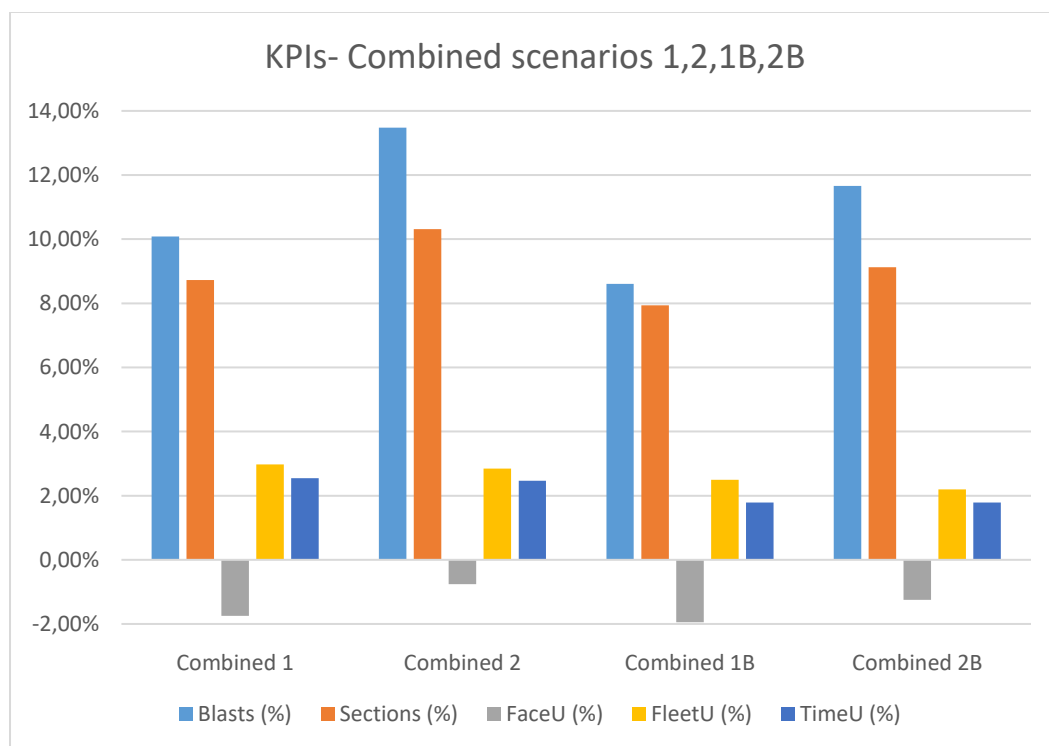


Figure 28 Simulation results for combined scenarios (1,2,1B,2B) compared to baseline

Simulation results of combined scenarios depicted in Figure 28 show the highest values for respective indicators when compared to previous cases. This is obvious, since combination of improvements increases production and utilization of machines and time. However,

there are some differences. These differences are due to changes in possible work time defined by Normal Shift and Shift III, and extended operating time of machines determined by maintenance. Production increase ranges from 8,61% up to 13,48% more than baseline. The highest increase in production which is for Combined 2 scenario is the result of more time spent by machines at working locations, their improved availability, and faster operating time of the bottlenecks. Increase in operated sections by 10,32% comes from more headings and quicker finishing of activities by bolters. Even though, there are 11 additional headings, face utilization declined by the least percentage. It indicates that machines can work more effectively, by finding new work areas and bolters are slightly debottlenecked. The biggest decline in face utilization (-1,94%) is for Combined 1B scenario. This situation is because of less possible work time given by shift schedule, and thereby work of vehicles is suspended more frequently.

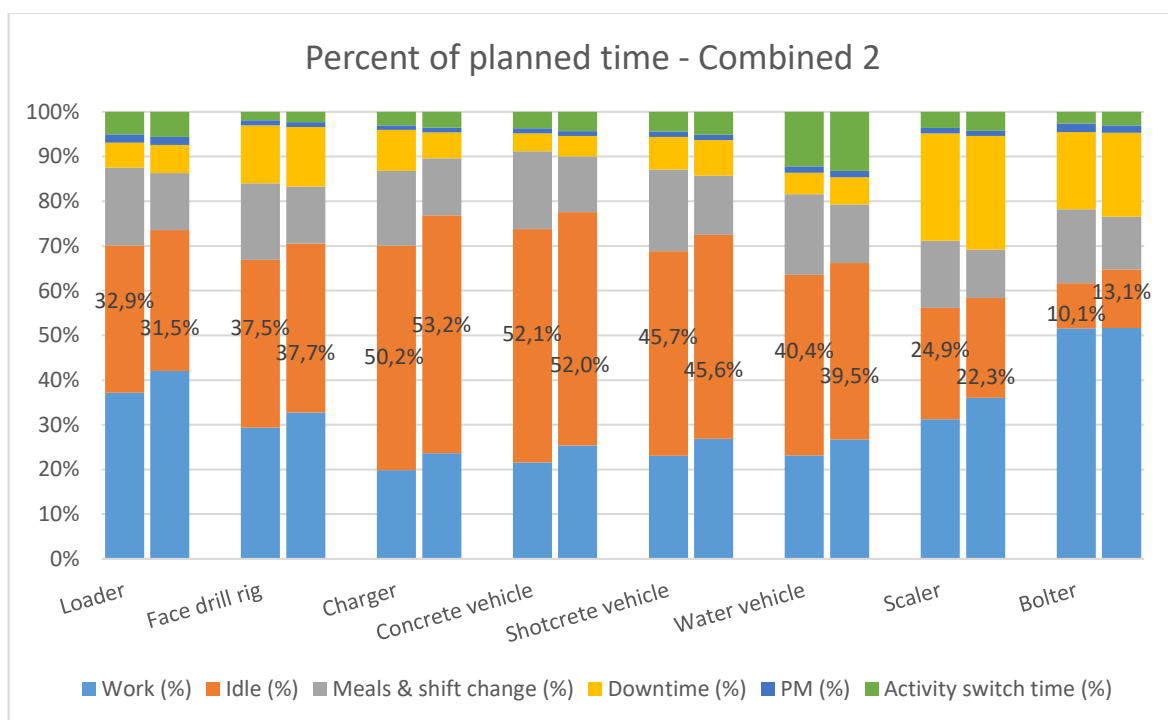


Figure 29 Fleet utilization data for Combined 2 scenario compared to baseline

Simulation results of fleet utilization for combined scenarios are presented in Figure 44 - Figure 46 in Appendix II. Results indicate gradual increase in vehicles utilization. Work performed by machines is a few percentage higher for every scenario, and idle time

is lowered. However, time spent on work by bolting rigs remains the same (Combined 2—see Figure 29, Combined 2B scenarios) or is slightly lower (Combined 1, Combined 1B scenarios). This is due to 10% faster operating time. Therefore, other machines might be higher utilized because of being given faster access to work location or by being dispatched to new ones, since additional headings are available.

For Combined 2B scenario where only maintenance is focused on bolting rigs, and at the same time possible work time is extended, machines tend to meet more disruptions during work and therefore downtime of some of them is increased; loader by 1,6% more, face drill rig by 1% more, shotcrete vehicle by 1,1%, and scaler by 2% more.

Combination of specific improvements within organizational, operating, and managerial aspects may highly influence utilization of machines within blasting cycle, and thereby, increase production. Combination of scenarios acts toward development of processes, by exploitation the bottleneck, subordinating plan to the bottleneck, and elevating system's bottleneck. Process of ongoing improvement might take some time to be fully implemented, however, simulation results imply that it is worth considering.

6 Scenarios correlation

Performed simulation scenarios indicate significant influence on blast cycle operations, concerning bottleneck and fleet utilization, time management, and production throughput. Analyzed scenarios can be categorized into technical and organizational group as an approach for improvements. Technical group includes cases like fleet maintenance, bolting rigs maintenance, and bolting rigs performance. Organizational group involves shift and blasting times and additional working places scenarios. Combined scenario may be treated as combination of technical and organizational cases. The aim of this paragraph is to analyze correlation between this two simplified groups of improvement aspects.

Both technical and organizational aspects act toward increase in production, however, there are some differences between results which are distinguishable.

Improvement of fleet maintenance extends the time of machines availability, therefore, vehicles can spend more time out of the workshop and continue with planned work. Fleet maintenance scenario also indicates higher exploitation of bottleneck. Slightly longer operating times of machines due to changes in blasting plan tend to act likewise. Little changes in shift times and blasting also exploits bottleneck to higher extent. For that reason, a correlation between improved fleet maintenance (PM and MTBF) and Shift III case can be seen. KPIs of these two cases show slight correlation. Shift III case indicates higher increase in production and face advance. This might be due to overall time extension in year scale, whereas in fleet maintenance case machines face more interruptions due to standard work plan.

Focus only on integrated maintenance of bolting rigs slightly increases exploitation of bottleneck and simultaneously facilitates more work for the rest of the fleet. There is a slight correlation between BRM scenarios and Shift II scenario, where bolters and other machines operate likewise. KPIs show little correlation between these two scenarios, where results for Shift II are higher for Blasts, Sections, and FaceU. Lower values of FleetU and TimeU suggest that fleet could be better utilized over total available shift work time in year scale.

Simulation scenarios regarding bolters performance show significant influence on bolting rigs utilization as well as on other machines. Increase in bolting efficiency by shortening of

operating times debottlenecks bolters and makes other machines busier. It translates into higher production and slightly better utilization of shift work time. Shift I scenario also indicates debottlenecked bolting rigs, while other machines including bolting can perform more work. But in Shift I case all machines are way idler than in all BP cases. Furthermore, despite there is increase in production for both scenarios, FleetU and TimeU results vary. It suggests that in Shift I scenario there is bigger potential for higher fleet utilization and time management when proper planning is performed. Therefore, correlation between these two cases is very low and can be distinguished only between certain indicators like fleet work percentage, but excluding bolters.

Organizational aspects regarding additional working places show high influence on overall fleet utilization including higher exploitation of bottleneck resources. Increase in production and other indicators is also noticeable. This scenario demonstrates low correlation or no-correlation with fleet maintenance case. Fleet utilization data shows no-correlation between these two aspects. In fleet maintenance case, minor part of machines including bolters are more utilized. In additional headings case, most of machines except one, are more exploited. KPI results are way higher for additional headings case than for fleet maintenance improvement, but still FaceU varies substantially. Therefore, very low correlation can be seen, especially for Blasts, Sections, and TimeU.

Similar situation is for bolting rigs performance. Fleet utilization data shows low correlation between this scenario and additional headings case. This correlation is visible for most of machines excluding bolters, but regards only time spent on work, where it is higher for each of the vehicles. But vehicles' idle state varies considerably from case to case. For KPIs results, correlation is also low and regards only Blast and Sections, whereas for other indicators distinct difference is noticeable. This difference might be caused because in the first case only bolting efficiency is emphasized, whereas in second case all machines in the cycle are influenced by planning and organizational changes.

Major and minor correlations can be seen between technical and organizational aspects. To obtain more optimized results with stronger influence on production and utilization of resources, broader investigation should be performed which will include more and different combinations between cases, that could be simulated.

7 Discussion

The main objective of this thesis was to identify bottleneck for underground blast cycle operations performed in Kristineberg mine, which is operated by Boliden Mineral. Subsequently, analysis of bottleneck was conducted what allowed to make some suggestions for improvements which were also included in the thesis's scope. The aim of analyzed improvements was to present a potential for development of operations carried out within the blast cycle and other aspects which affect blasting procedures. Improvement suggestions may help Boliden to focus on most important aspects regarding technical or organizational changes, and thereby undertake real endeavors for implementation what relates to drawing some financial decisions.

To perform bottleneck identification and study procedures concerning blasting operations methodology from TOC was derived. TOC as a bottleneck theory provides reasonable approach in bottleneck identification and helps to undertake some steps that will facilitate bottleneck mitigation. TOC allows to look at bottleneck problem from different perspectives, where focus is not only on technological conditions of used resources but it involves organizational and managerial aspects. TOC methodology found its application in mining industry what was confirmed by Baafi (2015), Van Heerden (2015), or Phillis and Gumede (2009). Though, TOC and especially five focusing steps concept was applied in this thesis, there were some limitations. Since underground blasting cycle consist of several operations where some measurements of processes were needed, TOC did not supply any analytical tool which could help to study performance of the system. For that reason, DES approach was implemented. DES involved usage of simulation software SimMine. SimMine allowed to perform simulations of complex operations which incorporate many variables like timing, vehicles, shifts and locations. SimMine is fully focused on mining operations, therefore, this tool provided accurate building of simulation model. This tool is known in mining industry and finds its application in evaluation of mining processes. SimMine facilitated execution of several simulations, where different scenarios could be performed. Simulation software was quite flexible and efficient. Since SimMine is event oriented software, this made computational time of simulations to be very effective. Simulation approach together with TOC concepts eased study process.

Simulation results indicated that bolting rigs are the most utilized vehicles within blasting cycle operations. Operating time of bolters to complete their activity is the longest, and their idle state is the smallest of all machines, therefore, they are critically constrained resources which are considered to be the bottleneck. Reasons for bolters to be bottlenecks lay within some technical aspects as well as organizational procedures, which impede bolting fleet from better utilization. Technical aspects include inappropriate handling of this machines what contributes to occurrence of minor or major faults which increase the downtime and decrease machines' availability. Moreover, moderate or low operating skills lead to waste of machines' efficiency potential. On the other hand, organizational procedures also affect bolting operations. Imprecise dispatching of fleet or shortages in manned machines decrease operating potential. Furthermore, lack of precise planning and too frequent work interruptions have negative influence on overall utilization.

Results of conducted simulations showed significant differences between proposed scenarios and baseline. Analyzed scenarios considered some assumptions that could improve technical and organizational procedures. Results indicated that there is substantial potential for development of processes especially from organizational point of view, that also acts toward bottleneck. Considerable increase in production and higher efficiency of machines was noticed. But, since computer simulation is only a way of imitation of real operations where high accuracy of simulation model is achievable, it does not reflect a hundred percent of reality. It is hard to predict miscellaneous occurrences in mining operations due to harsh working environment or geotechnical conditions. Another uncertainty is within operators who are influenced by changes in production. Computer simulation is simplified and does not consider random incidents, though, it generates almost accurate results, what was presented during model verification and validation. Because of that, trustworthiness of simulation results is always below 100%. 95% confidence interval of performed studies is $\pm 0,7\%$ for simulation results. These results are considered to be very good and are very close to outcomes of real activities.

An answer to one of questions asked in section 1.3 is that proper identification of bottleneck in underground mining operations is possible with available techniques. One of theses techniques is computer simulation which facilitates analysis of complex systems and provides comprehensive information regarding studied problem. However, to identify

bottleneck properly a suitable simulation software should be chosen which will reflect operations to the very high level when it comes to accuracy and where the logic behind modelled operations is preserved. To use computer simulation for proper bottleneck identification a credible data is crucial. For that reason, relevant information regarding respective vehicles, resources, and operating procedures is required. Data should be collected and filtered appropriately so that input parameters are precise. To gather appropriate data, information sources or other relevant measuring systems are necessary to be installed. This will provide realistic information that could be further used in simulation software. Simulation technique can be supported with other methodologies like TOC which was used in this thesis. Combination of techniques provides thorough investigation of problem where perception of analyzed operations can be broadened. Furthermore, it might be more beneficial to rely on combined approaches rather than opting only for one possibility. This provides higher assurance of obtained results. Therefore, wise utilization of analytical tools and methodologies concerning managerial and organization procedures support proper identification of bottleneck for underground mining operations.

8 Recommendations for future work

Since the main point of this thesis concerned analysis of bottleneck and further focus on improvement of system exploitation, some of work was out of the thesis's scope. In this thesis, no economic aspects of simulation scenarios were considered. Therefore, it is necessary to perform economic study of proposed changes that could provide comprehensive financial comparison which would allow to assess profitability as well as the choice of most beneficial scenarios. Furthermore, together with financial study an evaluation of effort related to changes implementation could be performed. Effort assessment will provide analysis of which scenario is the most possible to be implemented first, and which one needs the longest time due to technological or technical limitations.

As simulation results showed, bolters are the most constrained resources. Bolters are quite sensitive machines, and because of long operating times and very high utilization it is clear that these machines are subject to many maintenance problems and disturbances. Improvement of maintenance indicated nearly 2,5% higher production. It might be obtained if maintenance plan is emphasized only for bolting fleet. To achieve this, a special maintenance team could be created. This team would be skilled only in bolters maintenance both in workshop during PM and when machine needs abrupt fixing at working face. Also, machines operators could be trained to fix minor faults that occurs during work, but for that, some light spare parts should be supplied.

Focus on bolters maintenance might be very beneficial. But, increase in bolting efficiency provides very promising results as well. Reasonable increase (BP+5%, BP+10%, and BP+15%) might be achievable, but it needs development of handling skills and well-trained operators. Since skills differ from operator to operator, it is recommended to put effort in well specialized team that would only focus on bolting rigs. Bolting is a complex operation, therefore, skilled operators are demanded. This could go together with some aspects from integrated maintenance plan, where operators are fully focused on this type of machines. Specialization in machines handling and caution could work toward increase in utilization because of less downtime and more effective work. These two aspects focused only on bolters are recommended for Boliden's consideration.

Extending available shift work time gives very good results when it comes to production increment, but potential within machines is not fully used. Changes in shift times should be analyzed and discussed with working unions if modifications in working policy are applicable. But, this work extension is only 20 minutes more per shift for the maximum case where lunch breaks are preserved. Therefore, this extension might be obtained by faster dispatching of operators to working locations by omitting pre-work meetings. Pre-work meetings could be substituted with better communication during work or provide operators with shift work plan on paper. Operators of bottleneck machines could also stay slightly longer at working locations for cases where blasting is not performed during lunch breaks. This would require some compensation for operators whom work time is extended.

Furthermore, for shift scenarios where 2 blasting times are proposed, more work regarding adjustment of development and production plan is needed. This adjustment concerns equal distribution of work with proper dispatching of machines and arrangement of available resources. This work could be conducted with the use of Gantt Scheduler software. When it comes to development in dispatching of machines and quicker communication with operators, implementation of automated system that will support work distribution could be investigated.

Additionally, adjustment of development and production plan is needed when more working faces/headings are to be concerned. This case assumes similar recommendations as for changes in shift and blasting times. But, more work regarding recognition of potential working places should be performed. This recognition involves analysis of short term planning and accessibility to mine reserves.

Recommendations for future work would be a very good continuation of conducted simulations if management decisions concerning tentative implementation of scenarios are to be made. Work recommendations act toward better assessment of bottleneck improvements.

9 Conclusion

There are several possible techniques of identification constraints in the system which limit the production throughput and influence the performance within the working cycle. This thesis concerned identification of bottleneck in the blasting cycle operation, which is quite complex and involve many activities. Complexity of operations make it almost impossible to perform thorough analysis of the system manually, where are many variables and factors influencing overall performance. For that reason, computer simulation was used to ease the study process and decrease computational time. Furthermore, TOC concepts were used to support the analysis and find possible improvements. Assumptions derived from TOC allowed to test scenarios concerning blasting cycle activities, but also TOC methodology indicated some limitations within procedures on which blasting processes are based.

Though, computer simulation might be very accurate in representation of real operations, in reality several challenges or miscellaneous incidents may occur, what is hard to predict in the simulation model. Therefore, simulation results cannot be taken for one hundred percent. Nevertheless, verified and validated simulation model gave very good results. In this thesis, the aim of computer simulation was to identify constraints and demonstrate effectiveness of possible alternatives which improve blasting operations and where bottleneck is better managed and production results are elevated.

Simulation results (see Figure 15 and Figure 17) indicated that bolting rigs are the most constrained resources in the blasting cycle, and thereby they are the bottlenecks. Reasons for bolters to be the bottleneck are due to unused full potential of machines capacity, not being given more flexible and available shift work time, maintenance issues, and work interruptions. Simulated scenarios showed that bolting fleet could be utilized to higher extent what also positively influences other machines and increases their work performance.

Simulated scenarios indicated that improved maintenance of the whole fleet extends machines availability and makes machines busier. For MTBF+15% increase in production was 1,78% and bolters were better exploited. However, it might require a lot of time to distribute improved maintenance plan over so many machines. Therefore, focus only on

bolters' maintenance but including integrated plan might be faster to attain and results are also promising. For BRM+15% increase in production was 2,32%.

Another scenario which related to technical aspects of bolting machines indicated that increase in performance significantly increases production, where for maximum case BP+25% it was higher by 3,5%, and acts toward debottlenecking of bolters. While other machines are more utilized, bolters showed to be idler. Therefore, for that case some more work places could be demanded. But increase in performance requires high skills of operators or advance in bolting technology, especially for maximum cases.

Further analysis concerned changes in organizational aspects which influence procedures within blasting cycle. These scenarios assumed subordination of working plan and working procedures to the bottleneck resource. Hence, changes in working time and number of daily blasts, and additional working places were studied.

Scenarios which involved extending working time showed very interesting results. For Shift I increase in production equaled 10%, but machines even the bottlenecks were idler. Therefore, more work should be provided. But, this particular case included no lunch break, so it might be impossible to implement right away, or situation with automated or semi-automated machines could be considered. Besides Shift I, other scenarios also indicated that changes within shift might have a good effect on production and higher exploitation of bottleneck resources. For example, for Shift III case production rose by 4,83% and blasting plan included only 2 blasts per day. More available work time acts toward bottleneck utilization and increases productivity.

Scenarios with additional working places showed that there is potential in fleet resources to be more exploited, but for that improvement in planning is required. Additional headings act as a work buffer which provides working place for machines instead keeping them in standby position. Heading+11 case showed increase in production by 5,87% and better fleet and time utilization, 2,98% and 1,89% higher respectively. Additional headings scenarios confirm that work organization substantially influences blast cycle operations. Therefore, it implies that some limitations are outside vehicles characteristic and their performance.

The last simulation scenario involved combination of approaches. This idea assumed thorough implementation of possible improvements that regard several aspects within blasting cycle procedures. This might be treated as process of ongoing improvement (POOGI), what is done through application of TOC concepts. Simulation results of combined scenarios indicated that substantial increase in production is achievable, where machines are more exploited, and at the same time bolting rigs are slightly debottlenecked. Combined 2 scenario presented the highest increase in production, what resulted in 13,48% more than the baseline. But, it included maintenance of the whole fleet.

Respective simulation scenarios with emphasis on bolters utilization and production results can be seen in Figure 30.

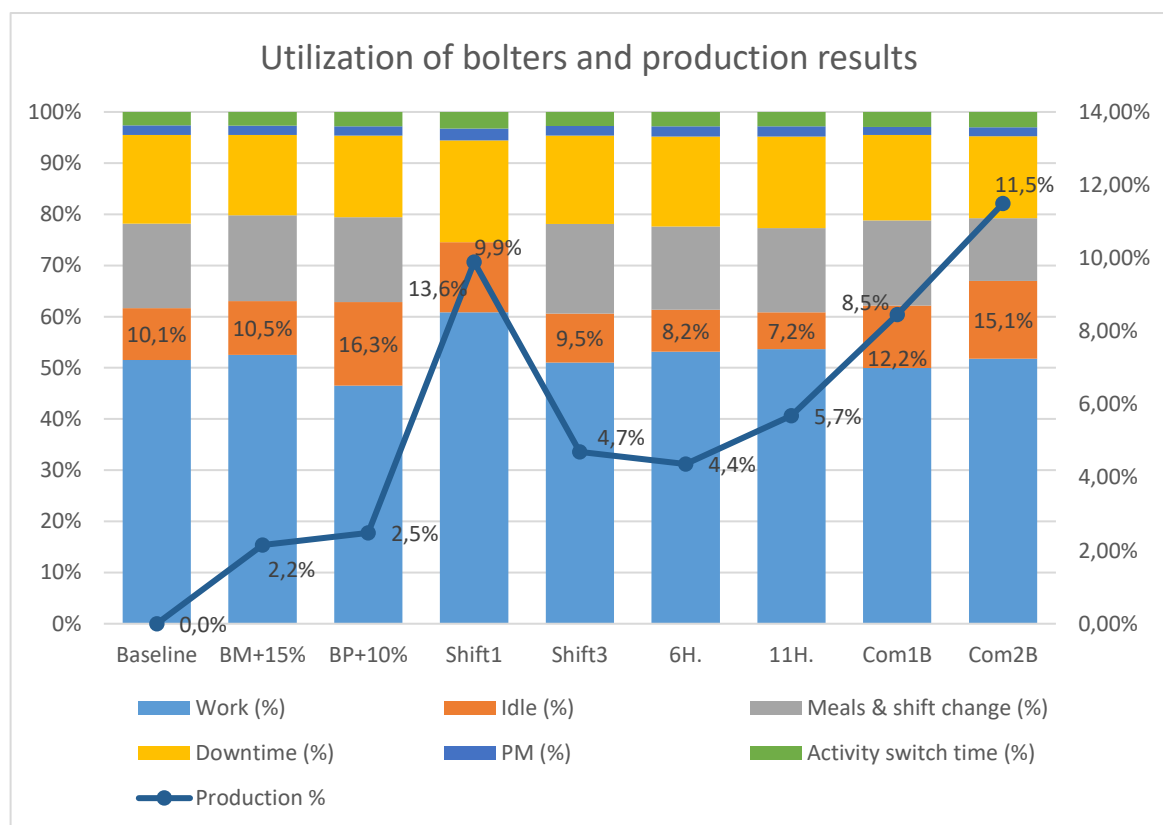


Figure 30 Bolters utilization and production results of chosen scenarios compared to baseline

Figure 30 presents interesting comparison of different scenarios and simultaneously shows how bottleneck resources are exploited and influenced by those changes. Simulation results indicated that bolters are simple bottlenecks type within blasting cycle processes,

but their operating efficiency might be elevated if some technical and organizational changes are implemented. One of these changes might involve additional headings. If 21-22 headings per week are provided for fleet to work on, production might increase by 5,7%. These 21-22 more headings are equivalent of scenario with 11 more headings, were in total 226 headings are planned for one year of production. Therefore, presented simulations show significant potential of improvements within blasting cycle operations and procedures, but some further work is recommended, what was described in chapter 8.

In this thesis, two approaches were combined. TOC methodology and computer simulation. Since TOC methodology which includes five focusing steps and thinking process provides good perception of bottleneck problem and managerial aspects, it lacks detailed analytical tools that could measure complex behavior of analyzed systems. Therefore, computer simulation was used to provide detailed analysis and support performance measures. Combination of these two approaches allow to perform broad analysis of the system where constraints can be identified and limiting factors recognized. TOC methodology with its tools allows to have wide perception of the whole work organization where many aspects are included. It involves technical, organizational, and managerial factors that influence operations. Therefore, problems might be recognized even outside the focus point. Supported by computer simulation may provide interesting study regarding many mining processes and working procedures. Computer simulation allows to perform analysis of different mining processes from exploitation, through ore handling and ending on processing. Computer simulation facilitates implementation of numerous scenarios where various configurations of resources, working schedules, vehicles, locations and facilities are possible to be tested. Simulation tools make it possible to build and examine extensive models of mining operations where mine layout is incorporated and reserves are defined. Additionally, advanced software packages including SimMine have cost calculators and allow to perform economic analysis. Scrutinized investigation of processes and testing different combination of prospective scenarios, is beneficial prior to new investment decisions or implementation of new solutions and systems. Therefore, combination of tools like TOC and DES helps to evaluate analyzed systems and contribute to improvement of mining operations where planning aspects are considered.

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Appendix

Appendix I: Input data parameters

Table 7 Weekly shift work plan in Kristineberg mine with actual work time

	Start	Stop	Start	Stop	Start	Stop	Start	Stop
Mon	6:15:00	9:30:00	11:00:00	14:35:00	16:00:00	18:45:00	20:00:00	23:30:00
Tue	6:15:00	9:30:00	11:00:00	14:35:00	16:00:00	18:45:00	20:00:00	23:30:00
Wed	6:15:00	9:30:00	11:00:00	14:35:00	16:00:00	18:45:00	20:00:00	23:30:00
Thu	6:15:00	9:30:00	11:00:00	14:35:00	16:00:00	18:45:00	20:00:00	23:30:00
Fri	6:15:00	9:30:00	11:00:00	14:35:00	16:00:00	18:45:00	20:00:00	23:30:00
Sat	6:15:00	9:30:00	11:00:00	14:35:00	16:00:00	18:45:00	20:00:00	23:30:00
Sun	6:15:00	9:30:00	11:00:00	14:35:00	16:00:00	18:45:00	20:00:00	23:30:00

Table 8 Working times for Shift I scenario

	Start	Stop	Start	Stop
Mon	6:30	14:15	16:15	23:15
Tue	6:30	14:15	16:15	23:15
Wed	6:30	14:15	16:15	23:15
Thu	6:30	14:15	16:15	23:15
Fri	6:30	14:15	16:15	23:15
Sat	6:30	14:15	16:15	23:15
Sun	6:30	14:15	16:15	23:15

Table 9 Working times for Shift II scenario

	Start	Stop	Start	Stop	Start	Stop	Start	Stop
Mon	6:15:00	10:00:00	11:00:00	14:30:00	16:00:00	18:45:00	20:00:00	23:45:00
Tue	6:15:00	10:00:00	11:00:00	14:30:00	16:00:00	18:45:00	20:00:00	23:45:00
Wed	6:15:00	10:00:00	11:00:00	14:30:00	16:00:00	18:45:00	20:00:00	23:45:00
Thu	6:15:00	10:00:00	11:00:00	14:30:00	16:00:00	18:45:00	20:00:00	23:45:00
Fri	6:15:00	10:00:00	11:00:00	14:30:00	16:00:00	18:45:00	20:00:00	23:45:00
Sat	6:15:00	10:00:00	11:00:00	14:30:00	16:00:00	18:45:00	20:00:00	23:45:00
Sun	6:15:00	10:00:00	11:00:00	14:30:00	16:00:00	18:45:00	20:00:00	23:45:00

Table 10 Working times for Shift III scenario

	Start	Stop	Start	Stop	Start	Stop	Start	Stop
Mon	6:15:00	10:00:00	11:00:00	14:30:00	16:15:00	19:15:00	20:15:00	23:30:00
Tue	6:15:00	10:00:00	11:00:00	14:30:00	16:15:00	19:15:00	20:15:00	23:30:00
Wed	6:15:00	10:00:00	11:00:00	14:30:00	16:15:00	19:15:00	20:15:00	23:30:00
Thu	6:15:00	10:00:00	11:00:00	14:30:00	16:15:00	19:15:00	20:15:00	23:30:00
Fri	6:15:00	10:00:00	11:00:00	14:30:00	16:15:00	19:15:00	20:15:00	23:30:00
Sat	6:15:00	10:00:00	11:00:00	14:30:00	16:15:00	19:15:00	20:15:00	23:30:00
Sun	6:15:00	10:00:00	11:00:00	14:30:00	16:15:00	19:15:00	20:15:00	23:30:00

Table 11 Working times for Shift IV scenario

	Start	Stop	Start	Stop	Start	Stop	Start	Stop
Mon	6:15:00	9:45:00	11:15:00	14:30:00	15:45:00	18:45:00	20:15:00	23:45:00
Tue	6:15:00	9:45:00	11:15:00	14:30:00	15:45:00	18:45:00	20:15:00	23:45:00
Wed	6:15:00	9:45:00	11:15:00	14:30:00	15:45:00	18:45:00	20:15:00	23:45:00
Thu	6:15:00	9:45:00	11:15:00	14:30:00	15:45:00	18:45:00	20:15:00	23:45:00
Fri	6:15:00	9:45:00	11:15:00	14:30:00	15:45:00	18:45:00	20:15:00	23:45:00
Sat	6:15:00	9:45:00	11:15:00	14:30:00	15:45:00	18:45:00	20:15:00	23:45:00
Sun	6:15:00	9:45:00	11:15:00	14:30:00	15:45:00	18:45:00	20:15:00	23:45:00

Table 12 Preventive maintenance changes

Interval [h]	Bolting Rigs	Scalers	Loaders	Drill rigs
Normal PM	200	180	200	210
PM+5%	210	189	210	220.5
PM+10%	220	198	220	231
PM+15%	230	207	230	241.5

Table 13 MTBF changes regarding micro faults

MTBF [h]	Bolting Rigs	Scalers	Loaders	Drill rigs
Normal MTBF	10	13	22	20
MTBF+5%	10.5	13.65	23.1	21
MTBF+10%	11	14.3	24.2	22
MTBF+15%	11.5	14.95	25.3	23

Table 14 MTTR changes regarding micro faults

MTTR [h]	Bolting Rigs	Scalers	Loaders	Drill rigs
Normal MTTR	1	1	1.1	1.1
MTTR-5%	0.95	0.95	1.04	1.04
MTTR-10%	0.9	0.9	0.99	0.99
MTTR-15%	0.85	0.85	0.93	0.93

Table 15 Bolting rigs performance parameters

Performance	Back slashing [min/length m]			Access drift [min/length m]			Production drift [min/length m]		
	Min	Mode	Max	Min	Mode	Max	Min	Mode	Max
Normal Bolter									
Drilling time	13.5	30.7	47.8	17.6	24.1	30.6	9.2	35.6	56.0
Bolting time	19.4	41.7	64.1	21.9	28.4	35.0	12.6	36.1	59.7
BP+5%									
Drilling time	12.9	29.1	45.4	16.7	22.9	29.1	8.7	33.8	53.2
Bolting time	18.4	39.6	60.9	20.8	27.0	33.2	12.0	34.3	56.7
BP+10%									
Drilling time	12.2	27.6	43.0	15.8	21.7	27.5	8.3	32.0	50.4
Bolting time	17.4	37.6	57.7	19.7	25.6	31.5	11.3	32.5	53.7
BP+15%									
Drilling time	11.5	26.1	40.7	14.9	20.5	26.0	7.8	30.3	47.6
Bolting time	16.5	35.5	54.5	18.6	24.2	29.7	10.7	30.7	50.7
BP+20%									
Drilling time	10.8	24.5	38.3	14.0	19.3	24.5	7.4	28.5	44.8
Bolting time	15.5	33.4	51.3	17.5	22.7	28.0	10.1	28.9	47.7
BP+25%									
Drilling time	10.1	23.0	35.9	13.2	18.1	23.0	6.9	26.7	42.0
Bolting time	14.5	31.3	48.1	16.4	21.3	26.2	9.5	27.1	44.7

Appendix II: Simulation results

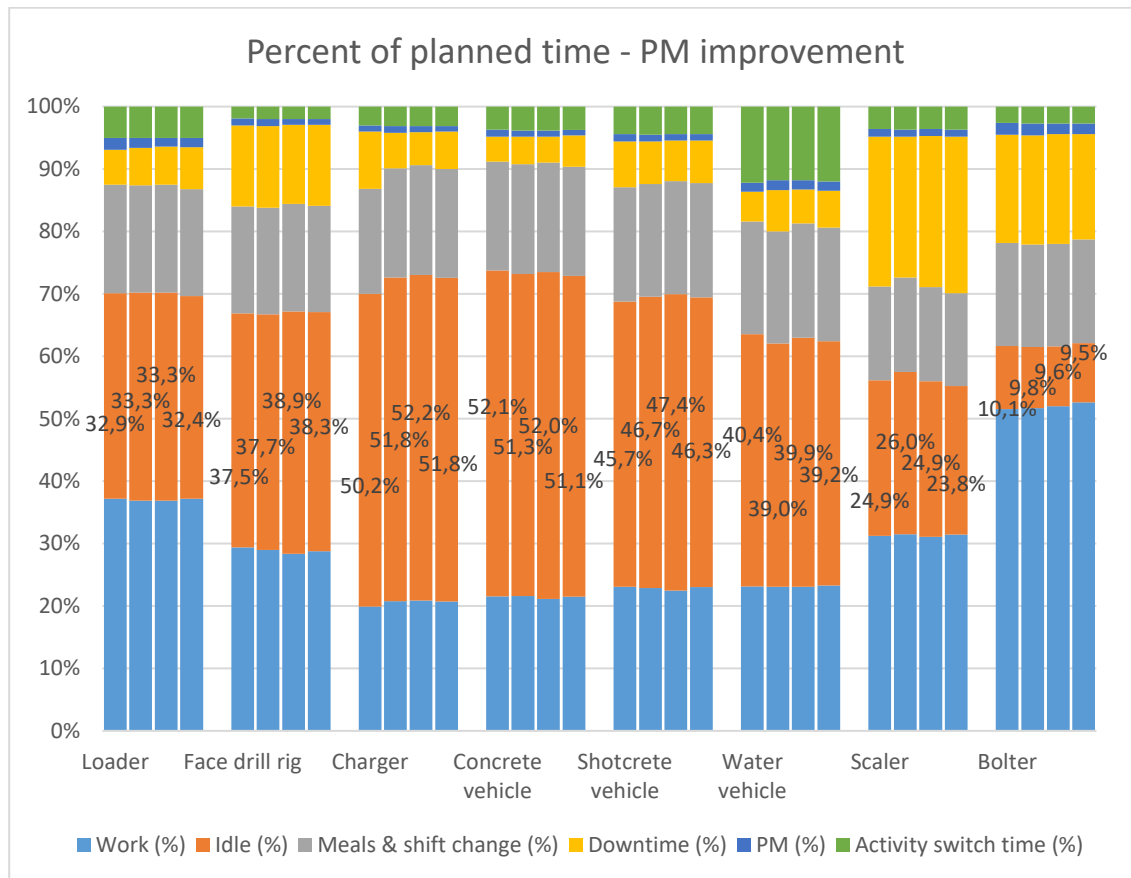


Figure 31 Fleet utilization data for improved PM compared to baseline

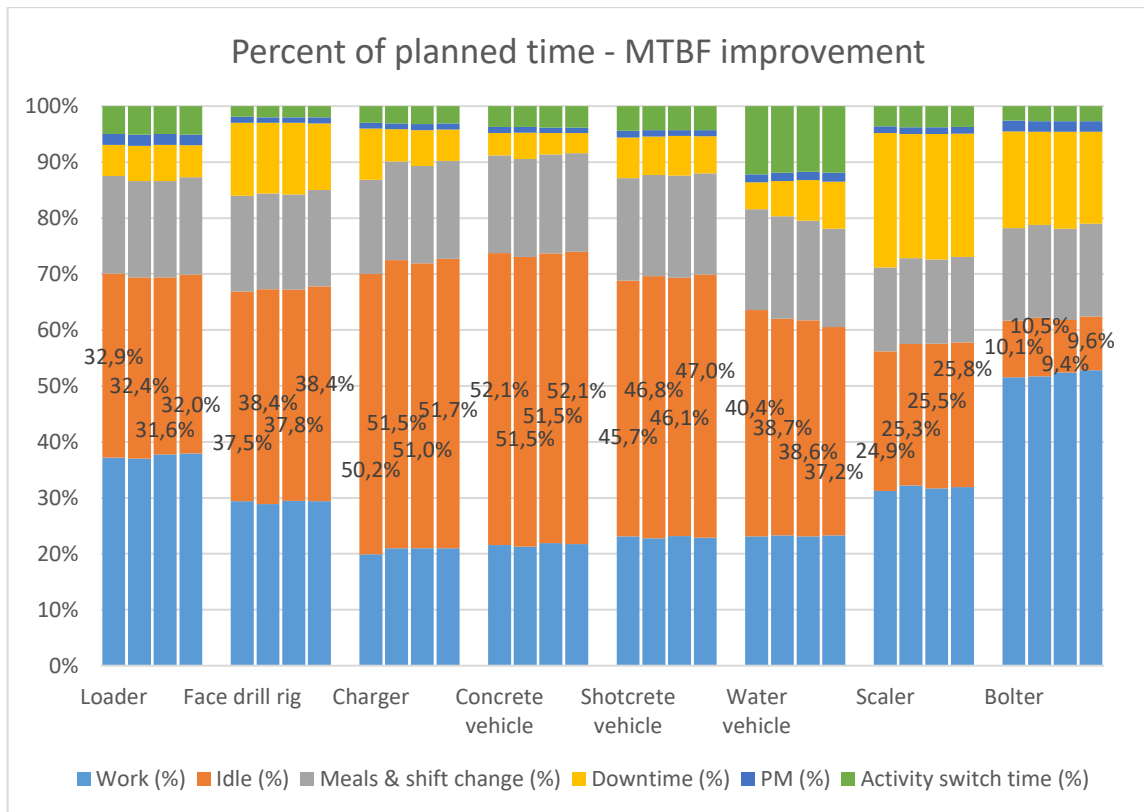


Figure 32 Fleet utilization data for improved MTBF compared to baseline

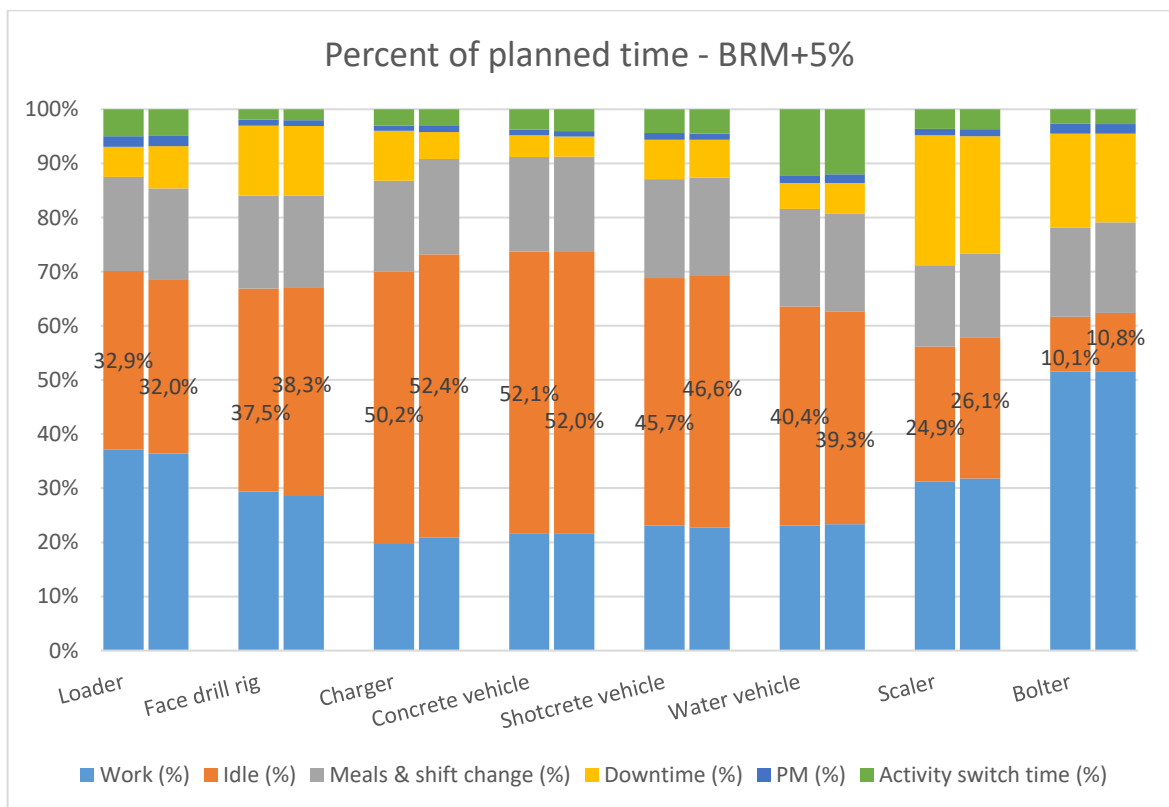


Figure 33 Fleet utilization data for combined maintenance (+5%) of bolting rigs compared to baseline

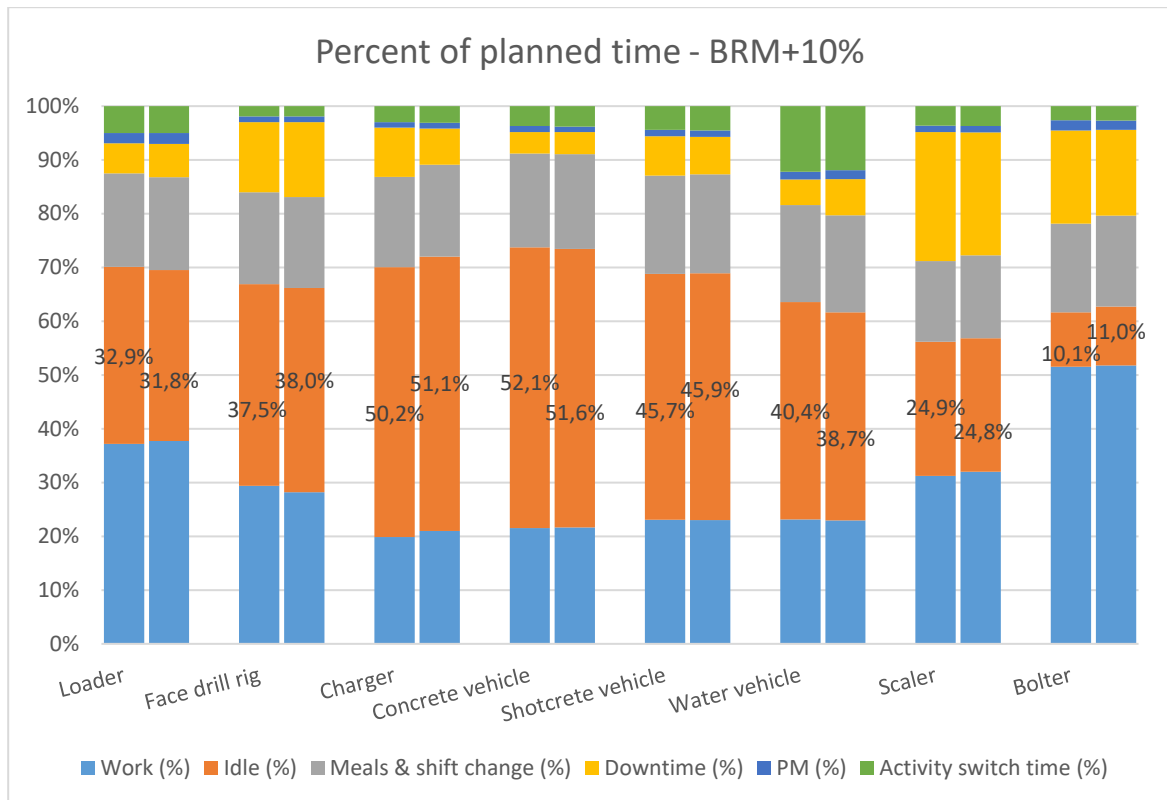


Figure 34 Fleet utilization data for combined maintenance (+10%) of bolting rigs compared to baseline

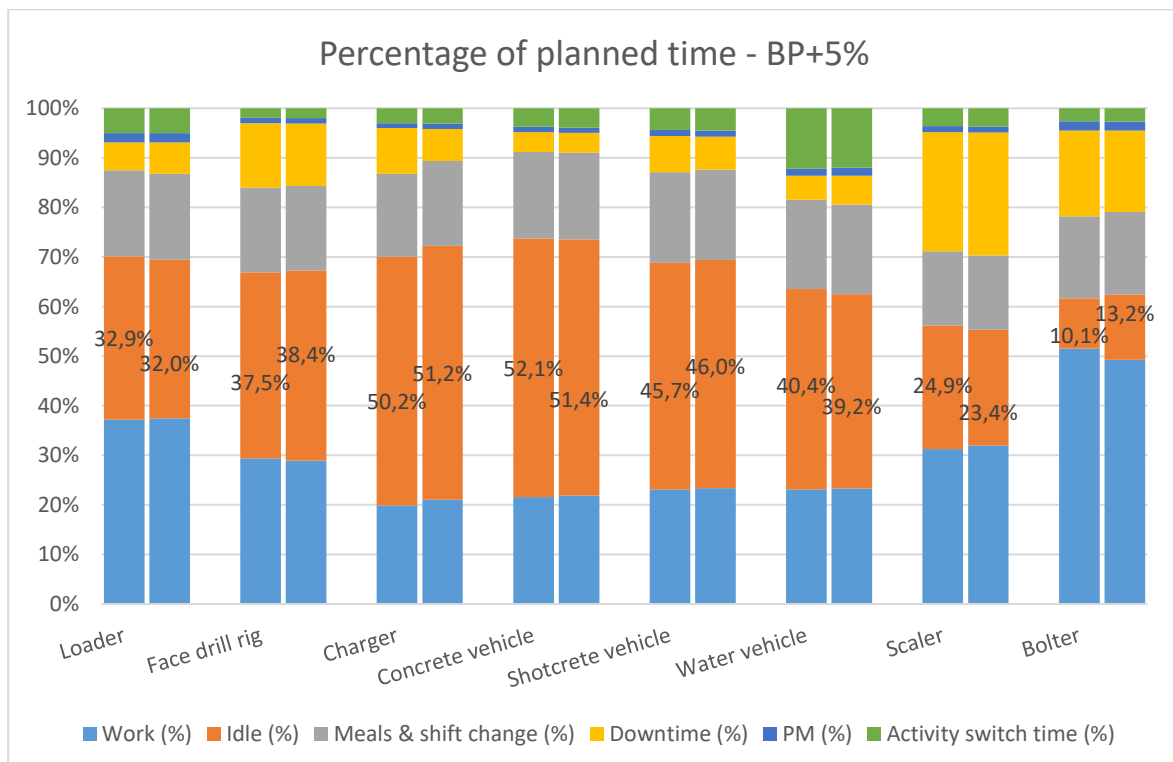


Figure 35 Fleet utilization data for improved performance (+5%) of bolting rigs compared to baseline

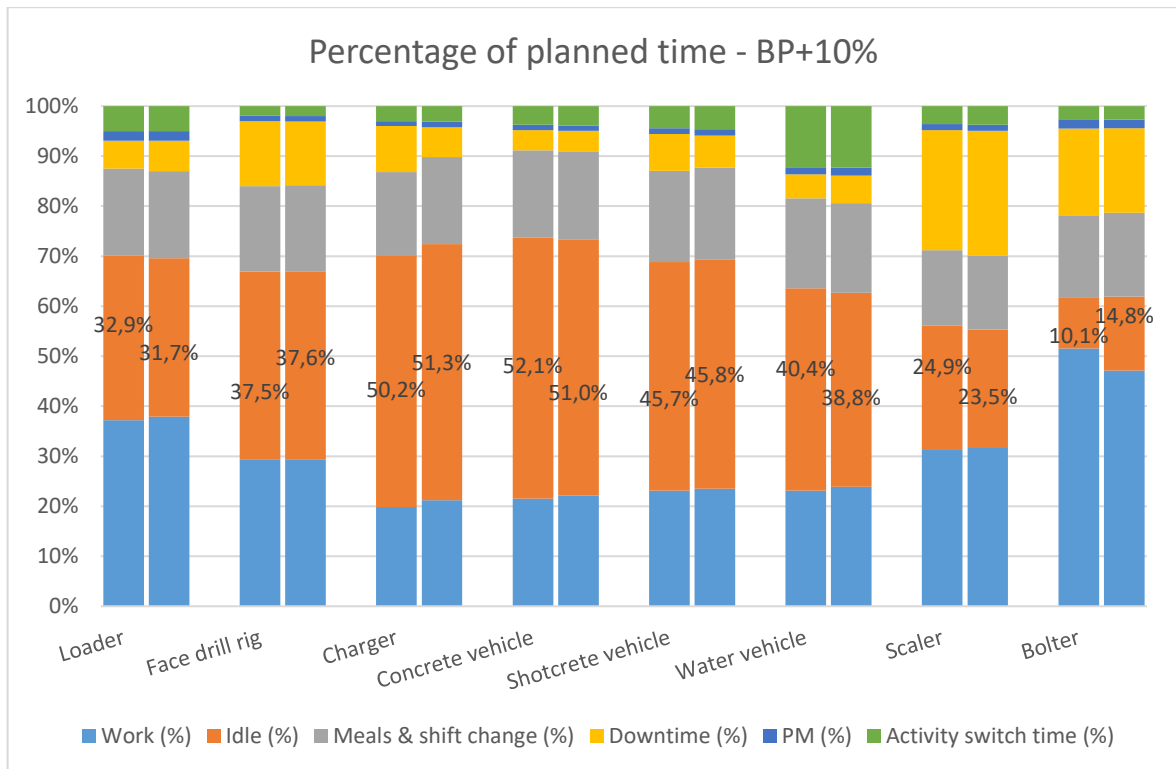


Figure 36 Fleet utilization data for improved performance (+10%) of bolting rigs compared to baseline

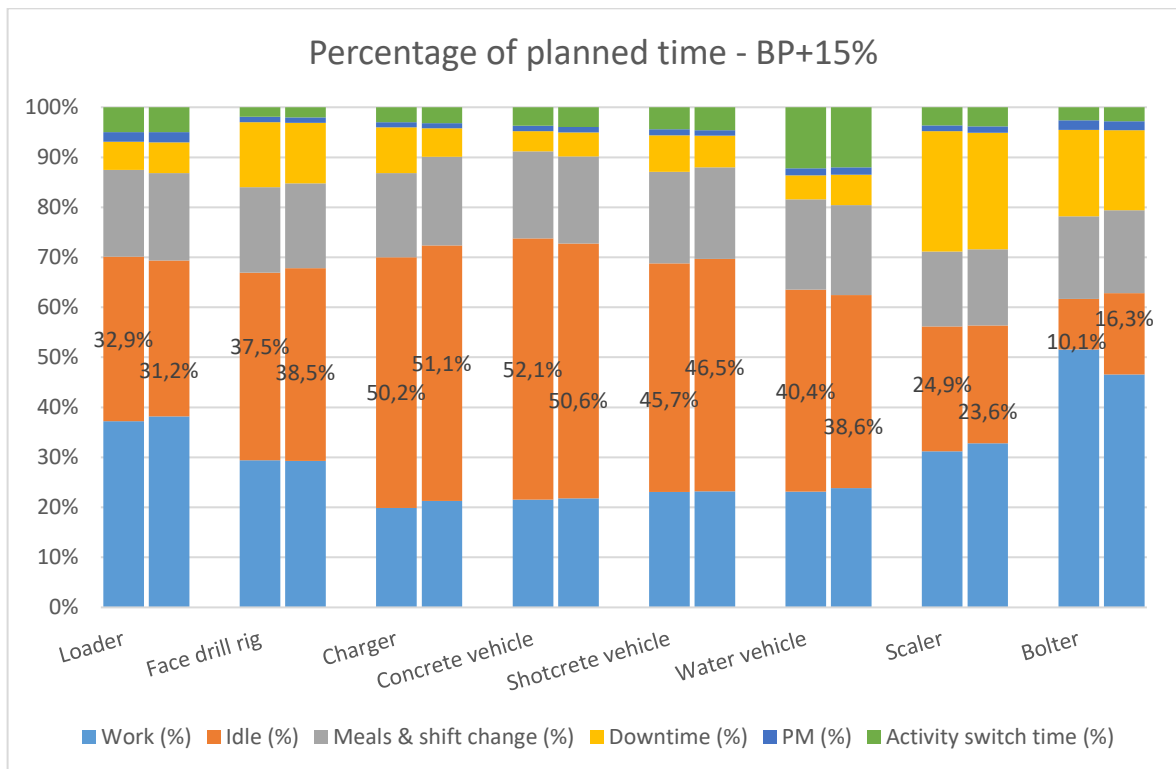


Figure 37 Fleet utilization data for improved performance (+15%) of bolting rigs compared to baseline

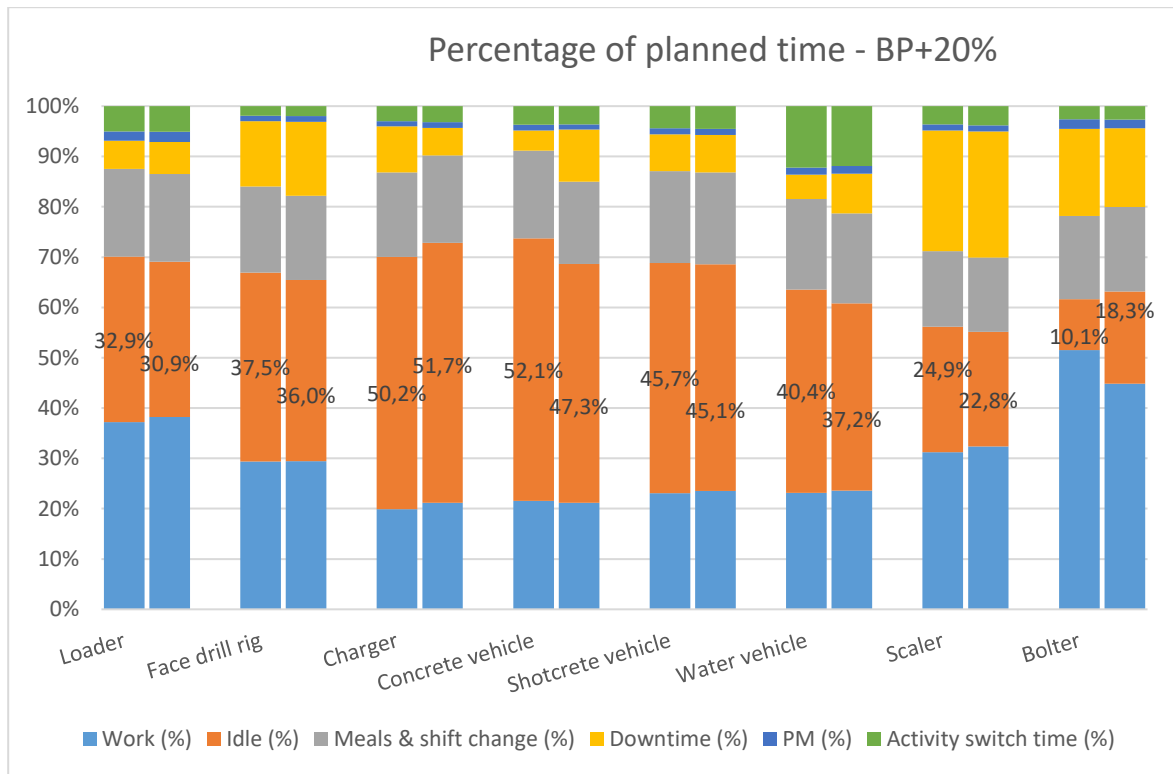


Figure 38 Fleet utilization data for improved performance (+20%) of bolting rigs compared to baseline

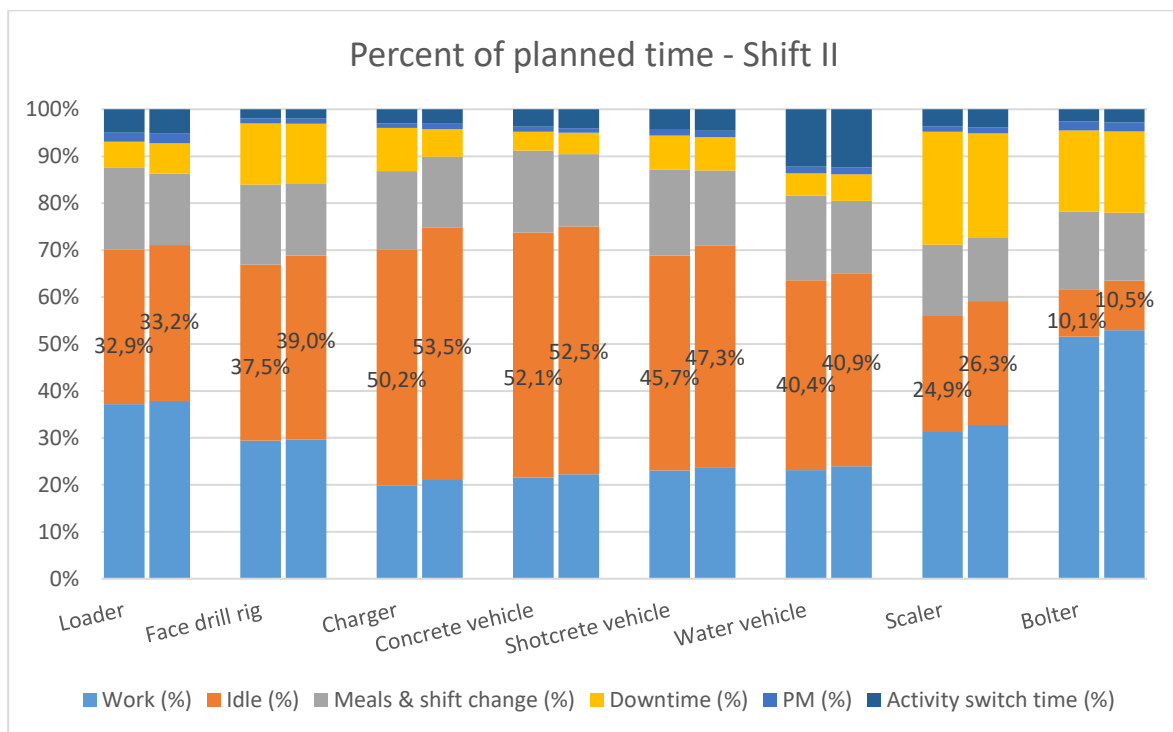


Figure 39 Fleet utilization data for Shift II compared to baseline

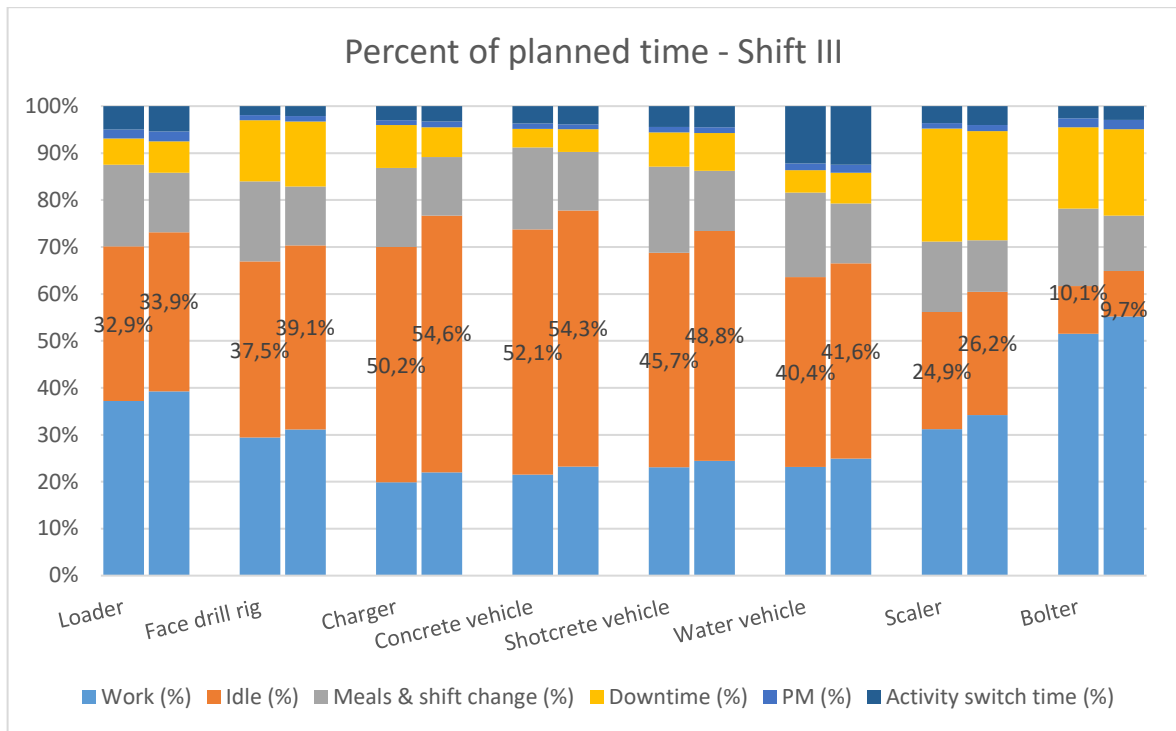


Figure 40 Fleet utilization data for Shift III compared to baseline

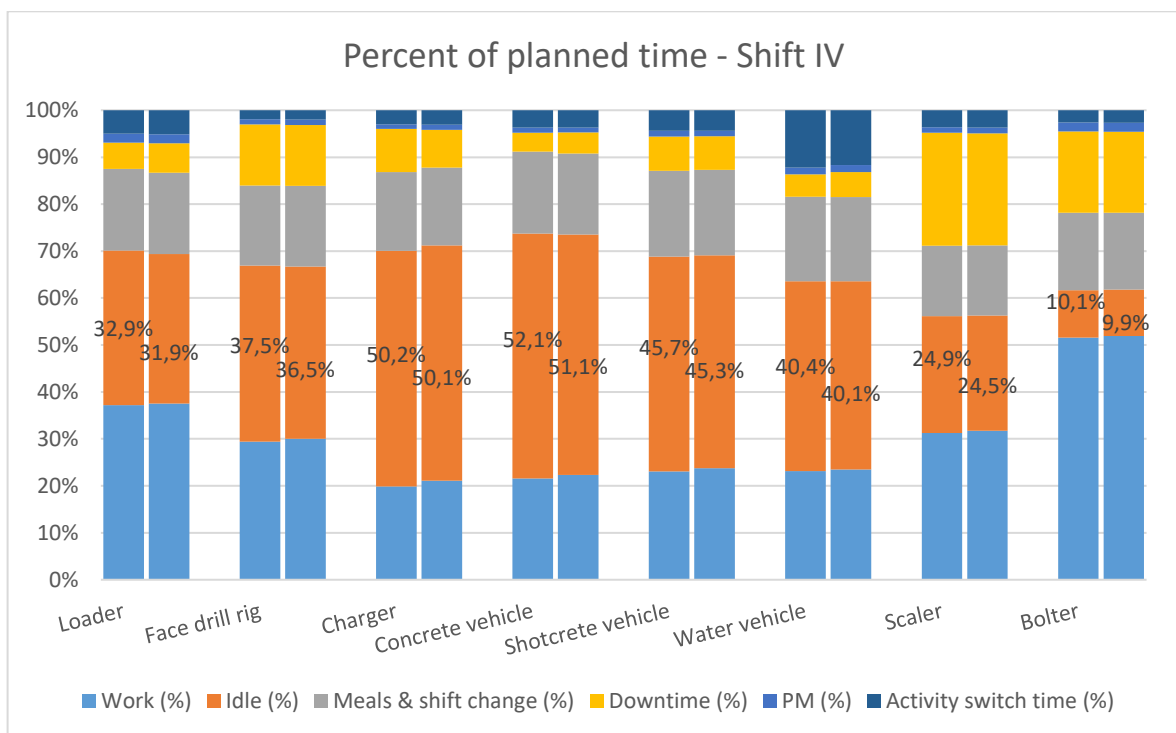


Figure 41 Fleet utilization data for Shift IV compared to baseline

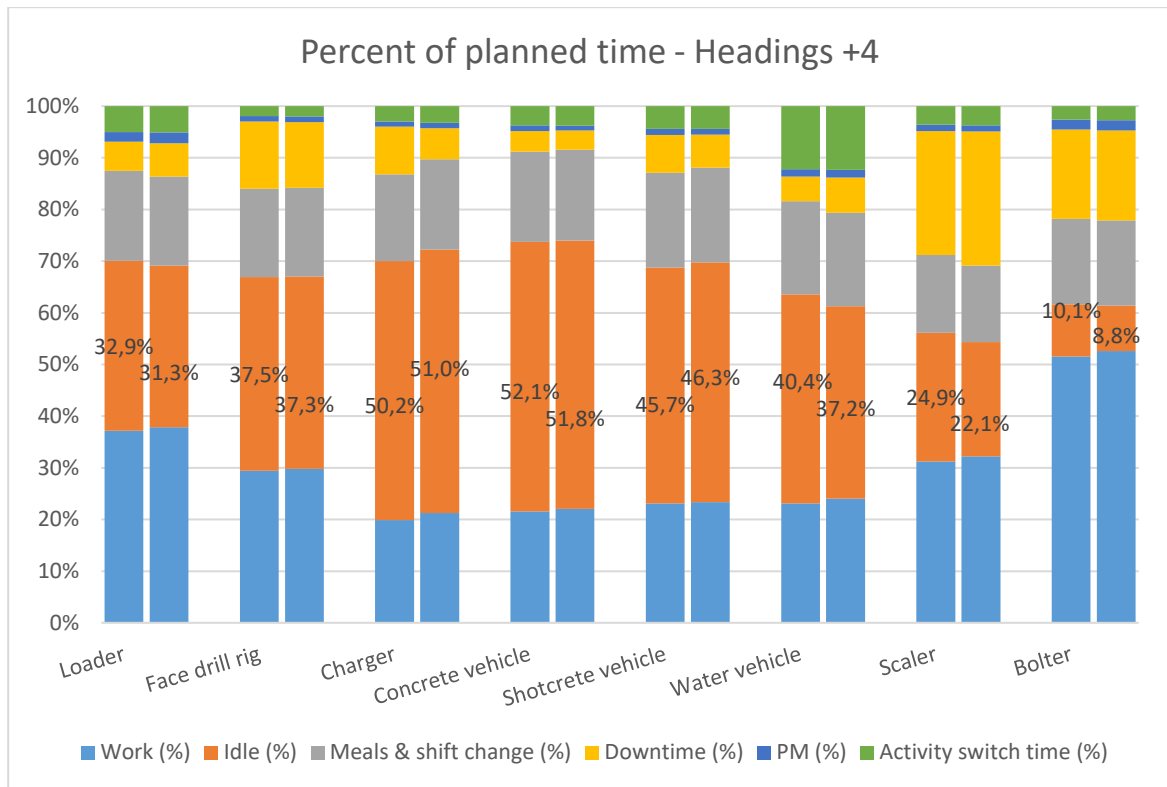


Figure 42 Fleet utilization data for 4 additional headings compared to baseline

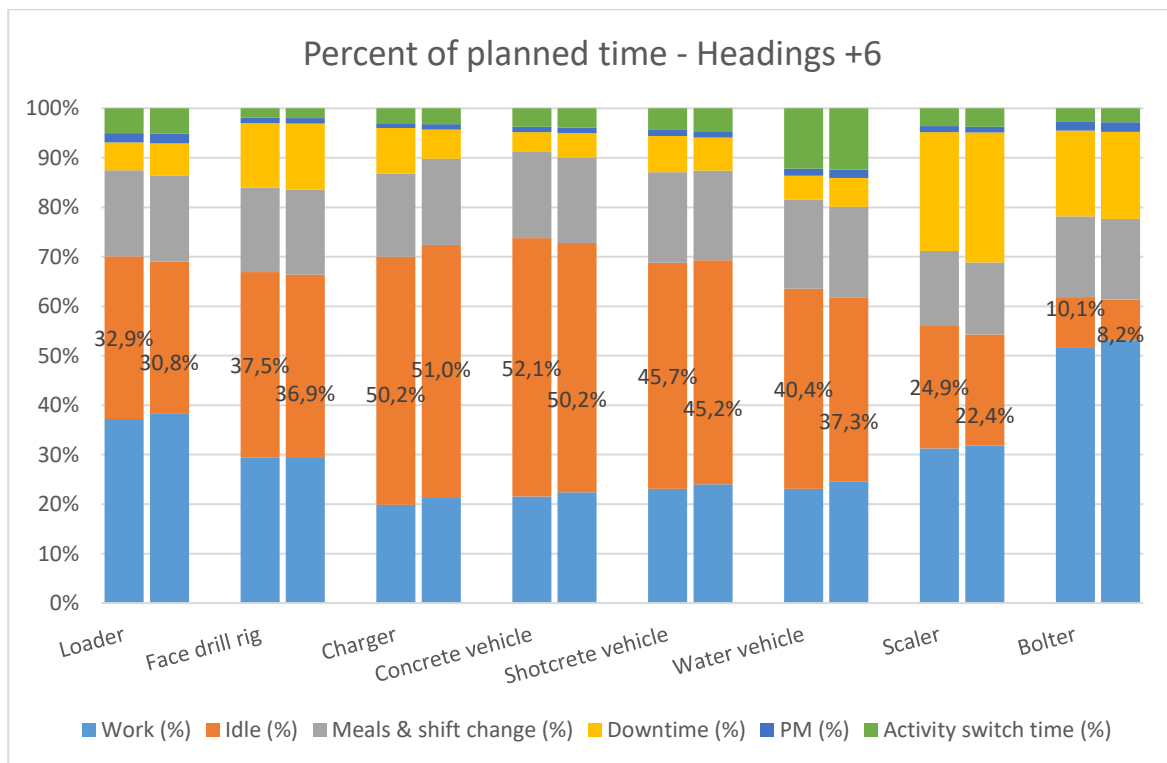


Figure 43 Fleet utilization data for 6 additional headings compared to baseline

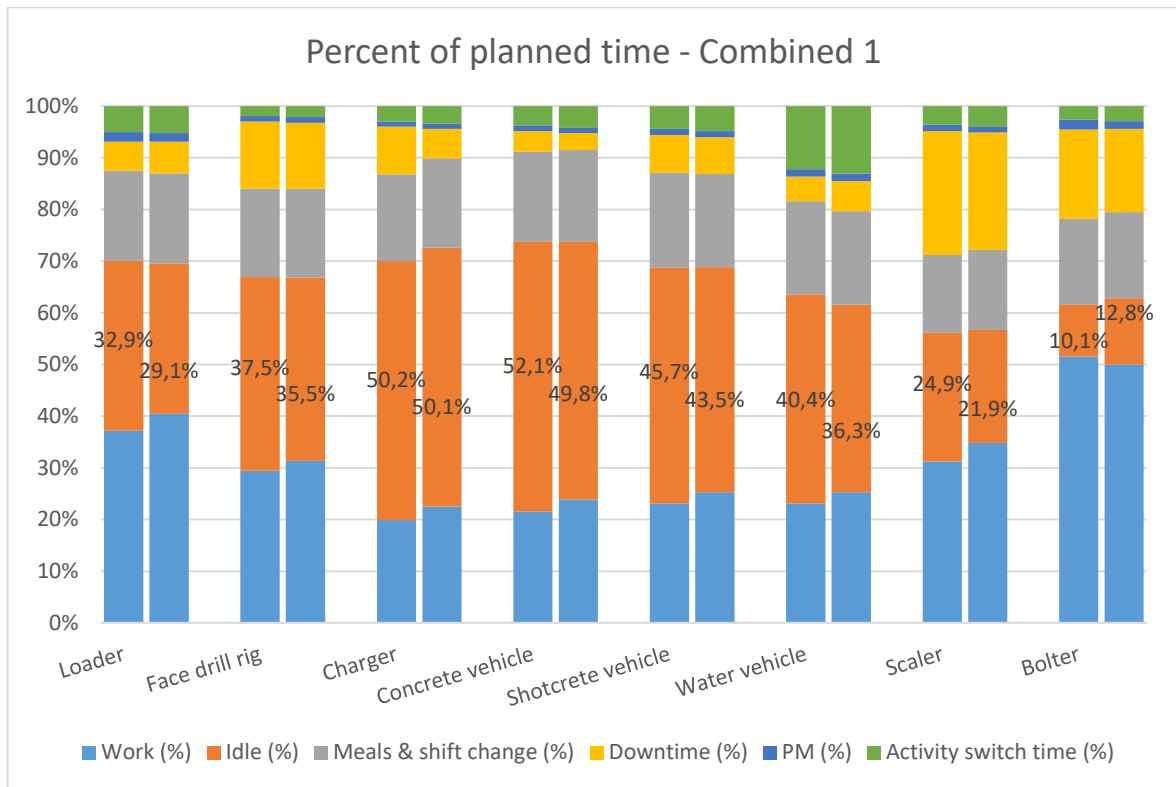


Figure 44 Fleet utilization data for Combined 1 scenario compared to baseline

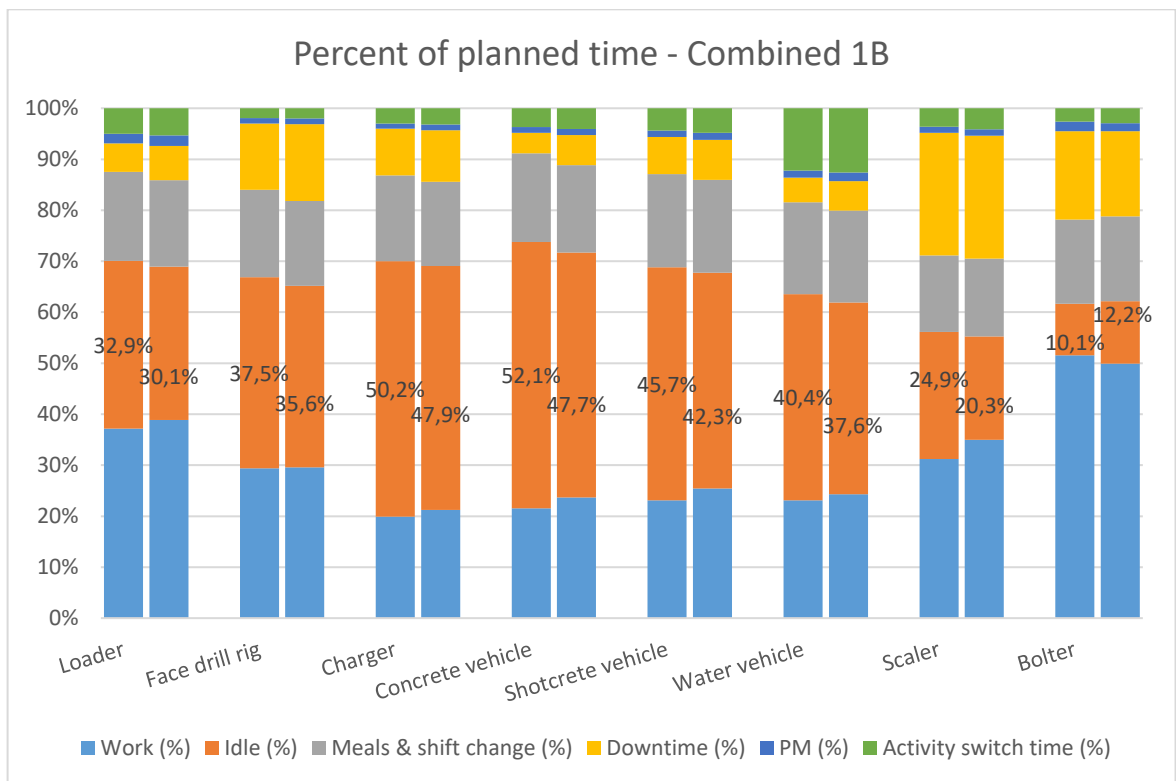


Figure 45 Fleet utilization data for Combined 1B scenario compared to baseline

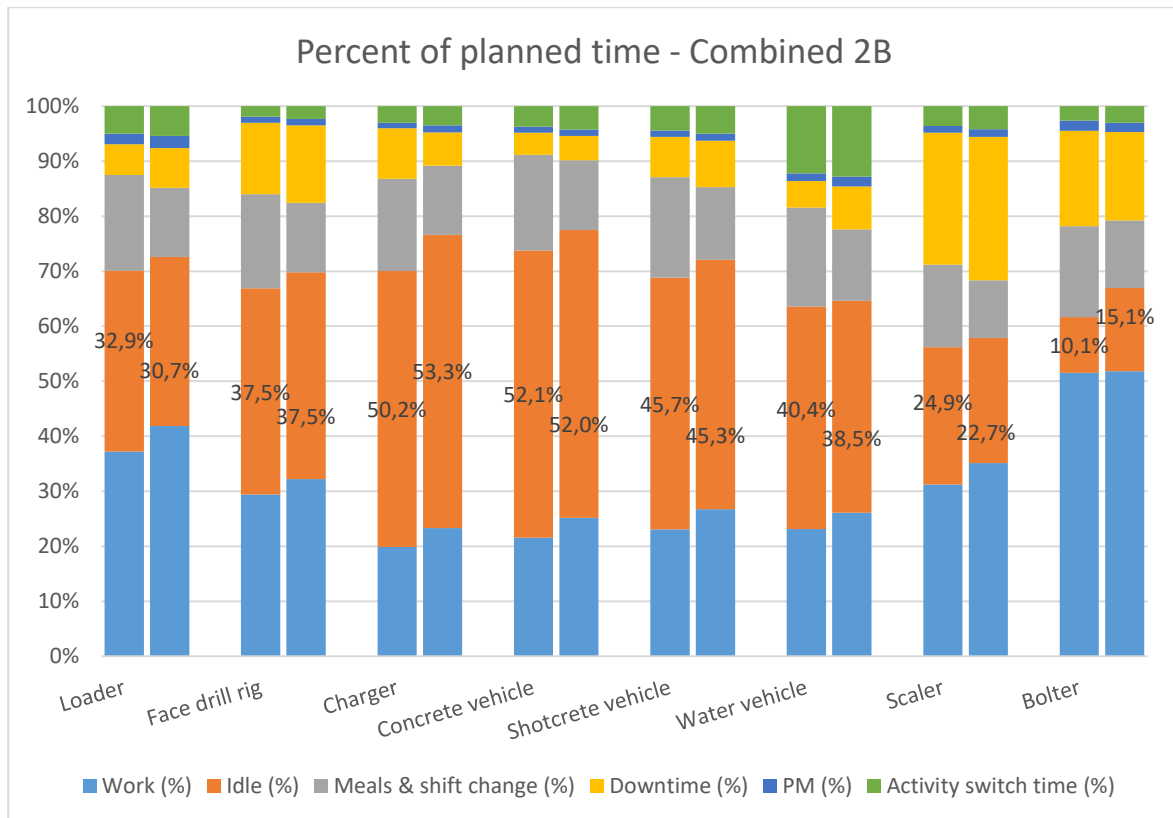


Figure 46 Fleet utilization data for Combined 2B scenario compared to baseline